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EARTH ORBITAL TELEOPERATOR SYSTEMS EVALUATION

1979-1980 TEST REPORT

CONTRACT NAS8-31848

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HUNTSVILLE FACILITY • 3322 Memorial Parkway South, Huntsville, Alabama 35801

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EARTH ORBITAL TELEOPERATOR SYSTEMS EVALUATION

1979 - 1980 TEST REPORT

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FOREWORD

Teleoperator system evaluations have emphasized operator/system research activities in three major laboratory facilities at the Marshall Space Flight Center (MSFC): the Teleoperation and Robotics Test Facility, the Visual System Evaluation Laboratory, and the Manipulator System Evaluation Laboratory. This report documents the activities performed by the Essex technical staff in support of those research activities, including development of test procedures, conduct and analyses of tests, and modifications to facilities and test equipment.

The successful accomplishment of the technical efforts would not have been possible without the involvement and dedication of Mr. Edward Guerin, the Contracting Officer's Representative. The participation of Mr. Keith Clark, Mr. Don Scott, and Mr. John Burch is also gratefully acknowledged.

The authors owe special appreciation to Mrs. Rebecca Stokes and Dr. Valerie Neal for their participation in, and contributions to, the Teleoperator Technology Development Program.

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ACRONYMS AND ABBREVIATIONS

dB	Decibel
DOF	Degree(s)-of-Freedom
Hz	Hertz
LOS	Line of Sight
LSS	Large Space Systems
MHz	Mega Hertz
MMS	Multimission Modular Spacecraft
MSFC	Marshall Space Flight Center
MU	Mobility Unit
OSU	Orbital Servicer Unit
PFMA	Protoflight Manipulator Assembly
RMS	Remote Manipulator System
SMM	Solar Maximum Mission
TMS	Teleoperator Maneuvering System
TRS	Teleoperator Retrieval System
Vdc	Volts, direct current

1.0 INTRODUCTION

The near term environments for remote systems operator performance data have increased dramatically as managers of flight programs perceive the advantages of remotely conducting some mission functions. Orbital insertion beyond the range of the shuttle, in-orbit inspection, servicing, repair and refurbishment, and satellite recovery are some of the pressing requirements that can be met through teleoperation. Certainly, the Teleoperator Retrieval System (TRS), which was under development to reboost Skylab, is a prime example of an immediate application of teleoperator technology.

This report addresses several areas which would have significant influence upon the engineering design of an operational teleoperator. In particular, it reports findings on teleoperator lighting systems, thruster systems, and stereoptic visual systems.

1.1 TEST OBJECTIVES

The prime objective of each of the following tests was to determine the effects, on human operator performance, of specified levels of several teleoperator subsystems. This objective differs from that of the usual engineering test where we are normally interested in performance of some hardware component in a system. In human factors evaluations, we are interested in the effects of, and on, the human component of a system; in remotely controlled systems, this is a critically important component.

Four evaluations are reviewed here, each dealing with operator performance under various task conditions.

1.2 SOLAR ILLUMINATION AND LIGHTING STUDY

The complexities of all possible approach and docking geometries are further compounded for the remote operator by introducing the geometry of direct solar illumination of the target. This study reviewed potential problems in viewing angles and visual recognition of target components with respect to high intensity illumination. The study also investigated some on-board teleoperator maneuvering system (TMS) solutions to the identified problems.

1.3 REMOTE APPROACH AND DOCKING STUDY

Remote control of a TMS will be affected by thruster pulse frequency, width or constant thrust mode, and thrust power. This study looked at the effects of thruster pulse frequency, approach geometries, and televised scene feedback on a satellite docking problem with a Multimission Modular Spacecraft (MMS) mockup.

1.4 STEREOPTIC DISCREPANCY STUDIES

Current stereoptic displays employ a two train visual system with each train individually calibrated. One question that arises is the effect of stereoptic train discrepancy on a human operator's perception of the task scene. One study dealt with the detectable limit of discrepancy and another dealt with operator performance of a task where discrepancy between two images was larger than the detectable limit.

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2.0 TELEOPERATION AND ROBOTICS TEST FACILITY

The Teleoperation and Robotics Test Facility is a versatile laboratory for integrated testing of teleoperator parameters. Not only can the several separate subsystems involved in teleoperation--visual systems, controller systems, propulsion systems, command and control systems, and manipulator systems--be integrated for testing, but specific environmental parameters can also be simulated in the facility. Target shadowing, solar illumination, effects of on-board lighting, and target approach and docking geometries are some of the environmental factors studied in the facility.

Two major tasks are reported here. One is an environmental study of on-board lighting, solar illumination and approach geometries, and the effects of these parameters on televised feedback of the task scene. The other study involves an investigation of the effects of different frequencies of thrust and various approach geometries on operator docking performance.

A detailed system description and laboratory specifications for the Teleoperation and Robotics Test Facility are contained in References 1 and 2. Study-specific equipment and laboratory modifications necessary for the conduct of the two reported investigations are described below.

2.1 TARGET ILLUMINATION

Critical components in any remote visual task conducted via television are the level and type of illumination on the target of interest. Shadowing, target sensitivity, image blooming, image contrast, and glare are some of the results of the interaction between the target illumination, both natural and artificial, and the sensor system. Preliminary information on the effects of solar and on-board scene lighting was developed in the Teleoperation and Robotics Test Facility utilizing full-size spacecraft mockups and a solar simulator.

2.1.1 Night Sun Solar Simulator

A Spectrolab Night Sun, SX/16, search light was installed in the test facility to serve as a source of simulated solar illumination. The light unit is a zenon plasma arc lamp that generates a peak beam of 30 million candle-power from an input of 28 Vdc at 65 amps. The lamp was mounted 3.2 m (10.5 ft.) above the laboratory's air bearing flat floor on a remotely controlled pan and tilt unit for target tracking.

The on-target illumination levels, as a function of light-to-target distance, shown in Figure 2-1, were generated during evaluations of the light system in the laboratory. The data were generated to determine the parameters required to produce 10,000 ft. candles at the target, the illumination level required for testing. It is apparent from the three power output curves

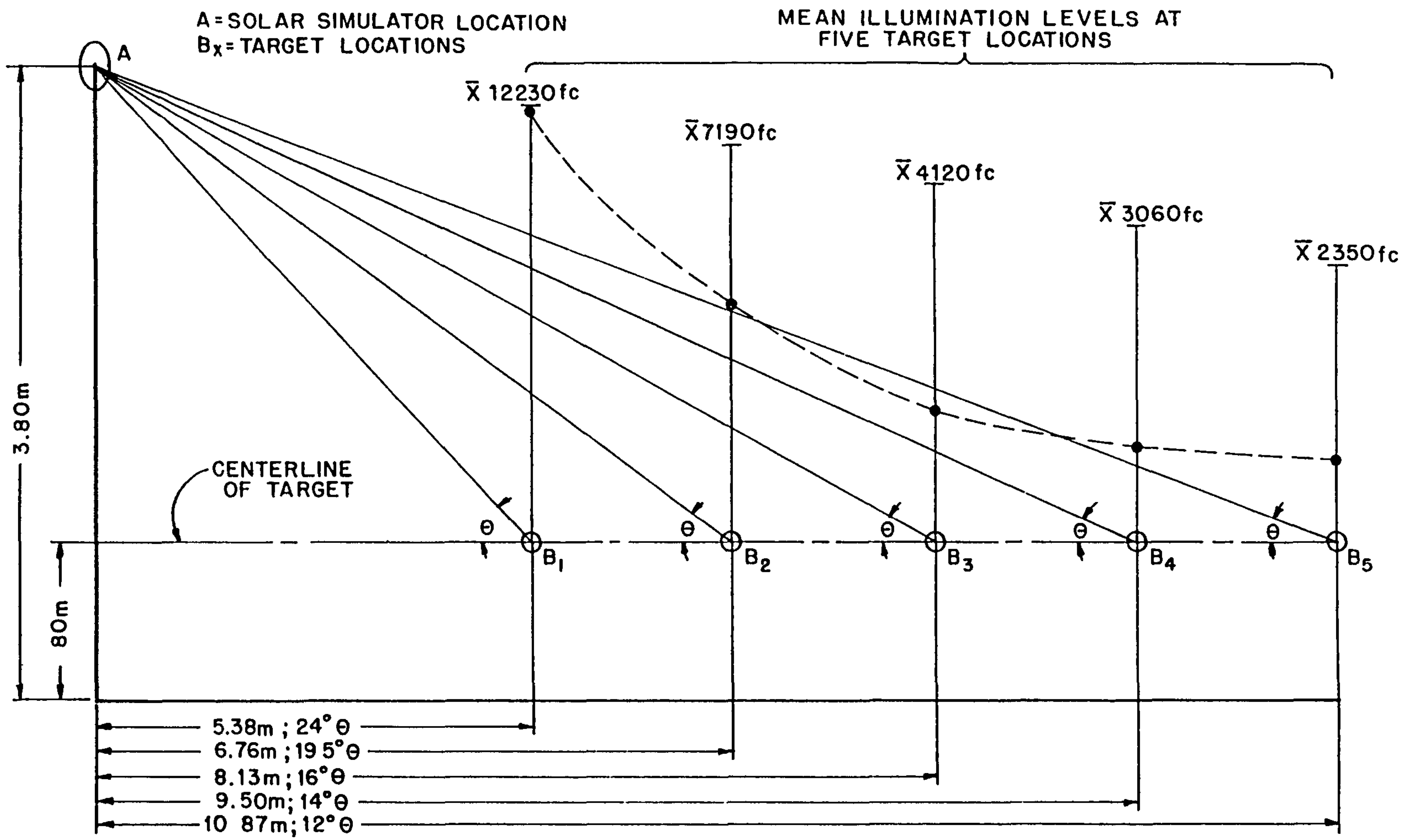

Figure 2-1: Target Illumination as a Function of Target-to-Source Geometry

(shown in Figure 2-2) that simulations of solar illumination yielding the required 10,000 ft. candles are restricted to a 6.1 m (20 ft.) range. With power supply modifications, however, it is possible to increase the operational range to 12.2 m (40 ft.) and with a variable rheostat to limit the illumination at the target to 10,000 ft. candles for distances less than 12.2 m (40 ft.). These modifications have been proposed in preparation for system evaluations during later testing.

The use of the Night Sun lamp requires some special considerations during testing. When the lamp is on, the temperatures at the lamp face range from 800° to 2100°F, creating a thermal hazard. While the lamp is mounted safely out of the work envelope of test personnel, moving the mockups too close to the light source could present a problem. Care must be taken not to allow the light beam to fall on a target that is close to the lamp. On-site inspection and control of the light are required during any test using the solar simulator. Secondly, the luminous energy of the lamp contains waves in the UV region so that protective eye goggles must be worn during operation in the vicinity of the lamp.

2.1.2 Multimission Modular Spacecraft Mockup

As part of the illumination study, a full-scale mockup of the Multimission Modular Spacecraft (MMS) was fabricated. This was done in accord with the mission plan requirement that the Solar Maximum Mission (SMM) satellite (one of the payloads of the MMS) be retrieved from orbit and returned to earth in the shuttle. Retrieval may be performed by the teleoperator and the shuttle manipulator, thus making the MMS an excellent candidate for approach and docking simulations. The MMS is highly angular in design, as shown in Figure 2-3, which gives rise to sharp shadowing from solar illumination.

The mockup was fabricated using overall configuration drawings, so there are some slight differences between the mockup and MMS, none of which affected the lighting study. To gain the required structural integrity and maintain low weight, the mockup was constructed from architectural Fome Cor®. Figure 2-3 shows the mockup as it was used in the initial lighting study, and Figure 2-4 shows the mockup outfitted with an insulating blanket of gold- and silver-colored foil and the star trackers. The blanketed mockup was employed in additional lighting evaluations, and in approach and docking studies utilizing the three docking pins mounted on the frame between each of the three subsystem modules.

While the MMS/SMM was selected because its mission profile requires retrieval from orbit, only the MMS section--the section to be grappled--was fabricated and used in the initial lighting study.

2.1.3 Teleoperator Retrieval/Multimission Modular Spacecraft Lighting Evaluation

The then current design of the Teleoperator Retrieval System (TRS) called for several large solar panels to be arrayed laterally about the TRS and for hydrazine fuel bottles to be mounted on the outside of the TRS body. The TRS

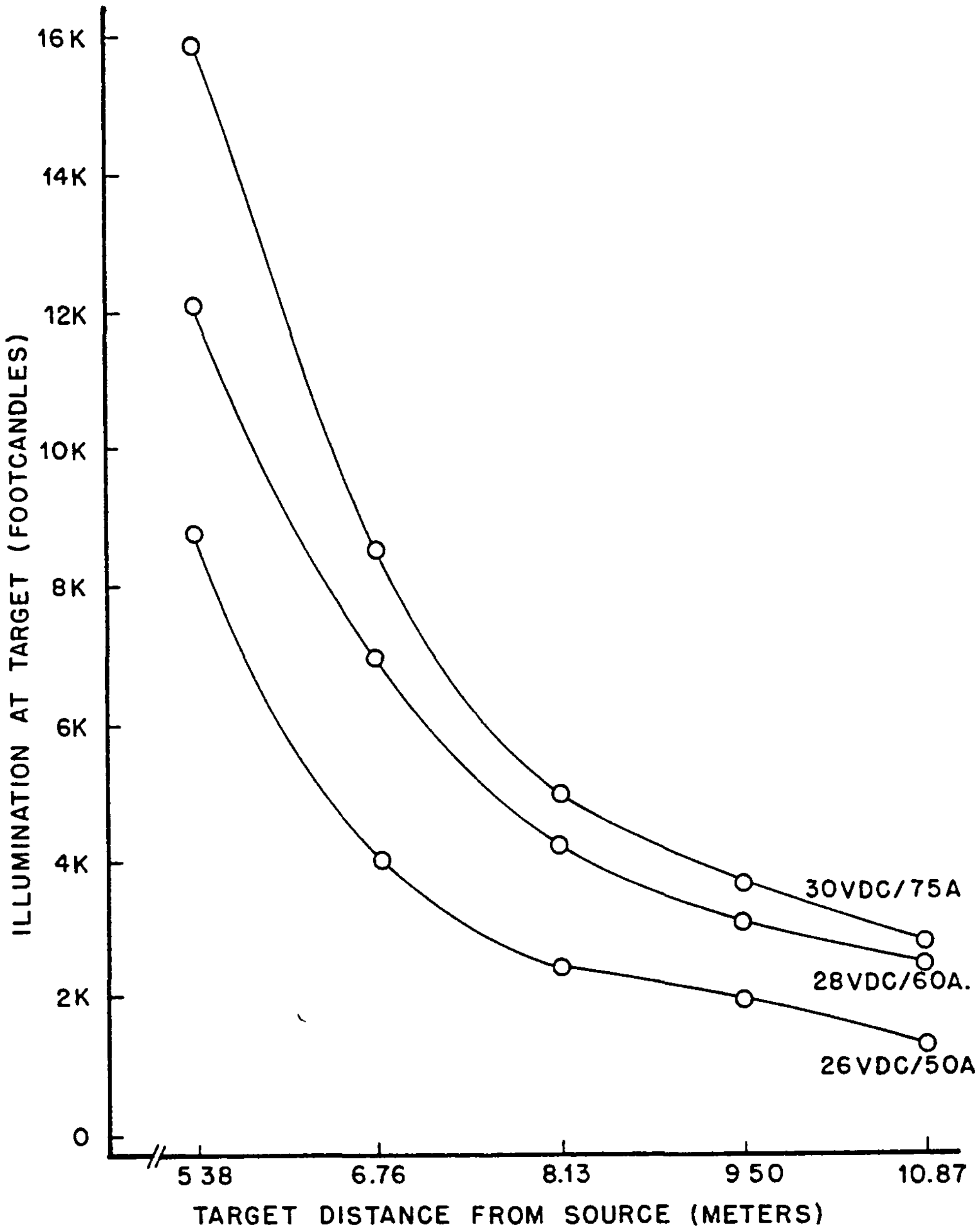

Figure 2-2: Illumination at Target as a Function of Target-to-Source Distance and Source Power Output

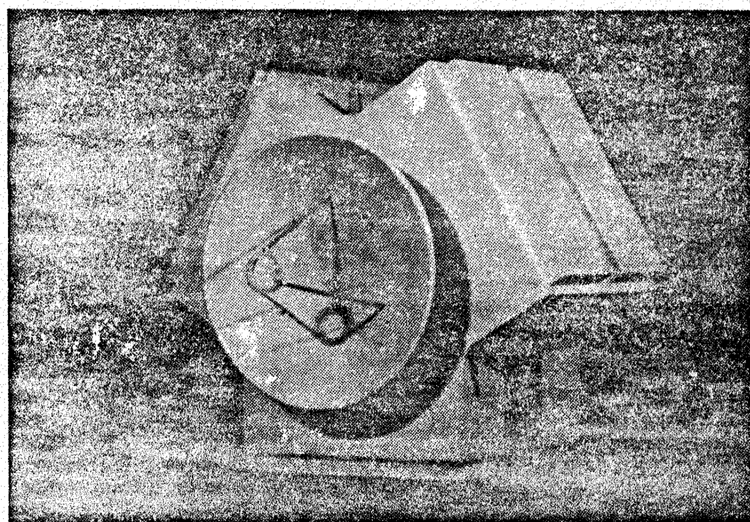

Figure 2-3: MMS Mockup Configured for Initial Lighting Study

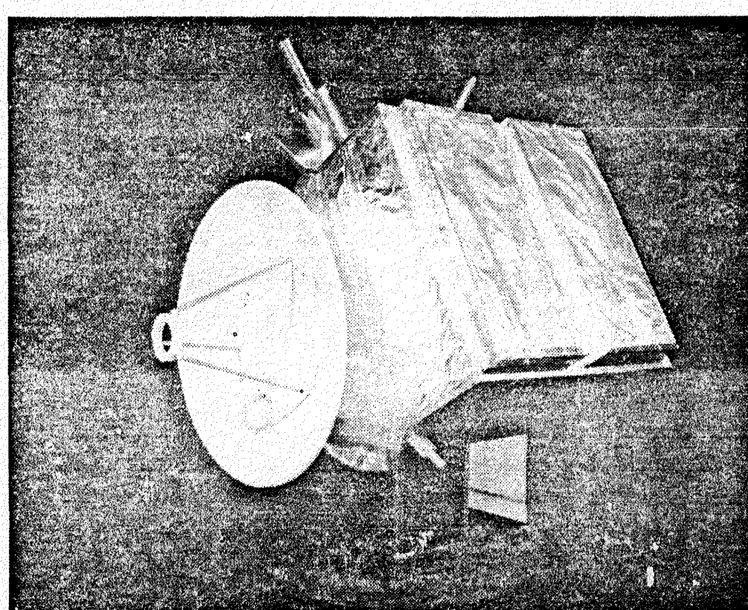

Figure 2-4: MMS Mockup Outfitted with Insulation Blanket

mockup geometry of three solar panels and two fuel tanks is shown in Figure 2-5 as it was used in the lighting evaluation study. The solar panels and fuel tanks were used to study the effects of shadowing on the MMS mockup when sunlight is coming from behind the TRS and is being obscured by these structures. TRS on-board lighting was provided to evaluate the amount of on-board lighting required to overcome shadowing on the MMS for appropriate target definition during approach and docking maneuvers.

The on-board camera for the TRS is shown projecting through the solar panel at the apex of the TRS body (Figure 2-5).

2.1.3.1 Procedure

The MMS mockup, without insulating blanket, was mounted on an air bearing target stand as shown in Figure 2-6. In order to investigate different TRS/MMS approach geometries, the target stand permitted target translation along the X and Y axes and target attitude manipulation in roll and yaw.

The TRS mockup was mounted on a roller pad for adjustment in the X and Y translation axes. For this evaluation, the TRS and MMS were aligned with each other along the center line of their approach plane, simulating final approach.

The TRS was equipped with three 150 watt flood lamps that could be turned on individually or in any selected combination. Figure 2-5 above shows two of the on-board lights located below and to the left and right of the video camera, and the third co-located with the camera.

All test equipment was situated on the flat epoxy air bearing floor, enclosed in the Teleoperation and Robotics Test Facility. The flat floor layout is shown in Figure 2-7.

The TRS video link was transmitted to the operator's control room shown in Figure 2-8. The picture on the TV monitor was photographed to record the lighting and shadowing on the target as a function of selected parameters. The video sensor was set to a peak white of 0.8 reflectance prior to the evaluation, and the camera iris was set to the automatic mode to allow the system to self-adjust as a function of target lighting and shadowing.

Because this was an initial lighting study to gather baseline data on target illumination, no test subjects were used in testing. Rather, the TV monitor images were evaluated by technical staff members, and photographs were used to record the effects of illumination parameters. This data base will be used to develop further lighting evaluations by using a wider range of sun angles, types of on-board lighting, and approach geometries.

2.1.3.2 Results

The results of the lighting evaluation are given in the collection of photographs (Figures 2-9 through 2-30) that record the images from the TV monitor in the control room. Each set of photographs shows the effects of

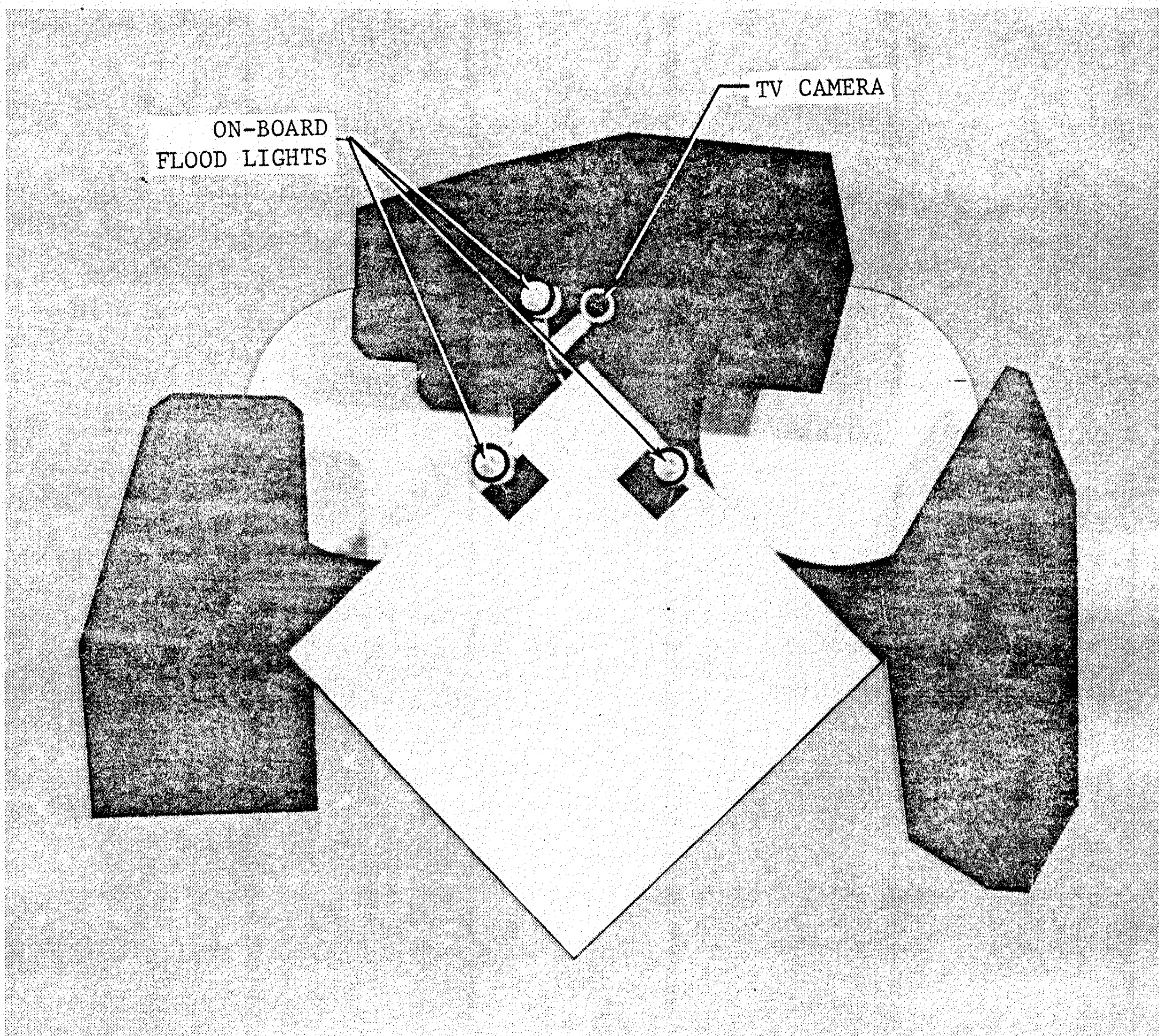

Figure 2-5: TRS Mockup Used in TRS/MMU Lighting Study

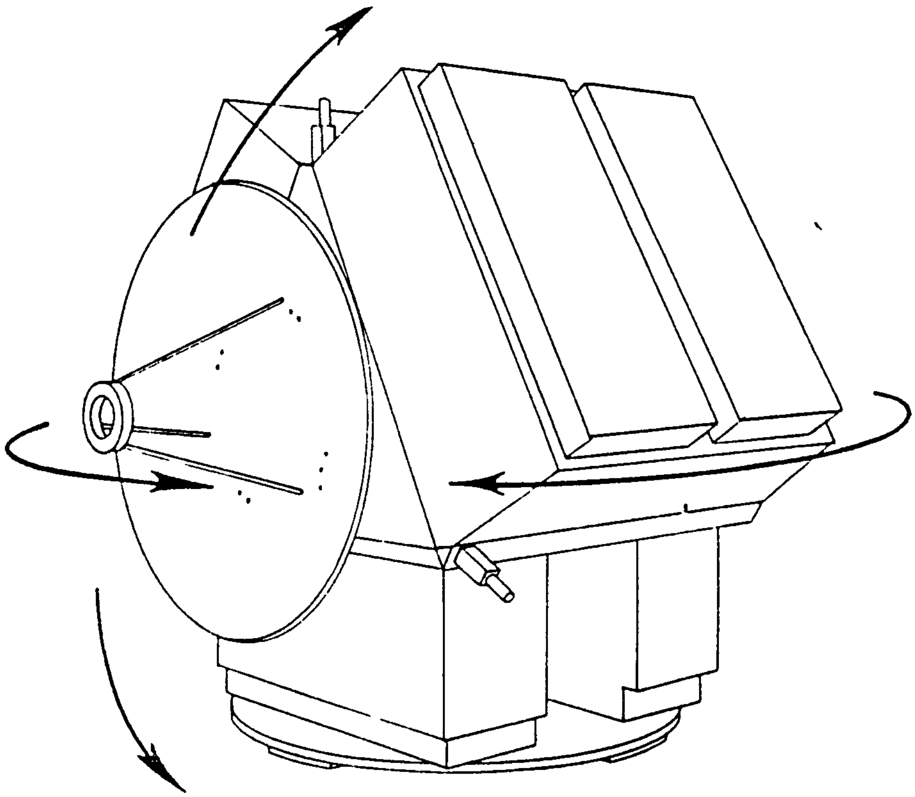

Figure 2-6: Air Bearing Stand with Attached MMS Mockup.
Five Axis Orientation Is Currently Possible.

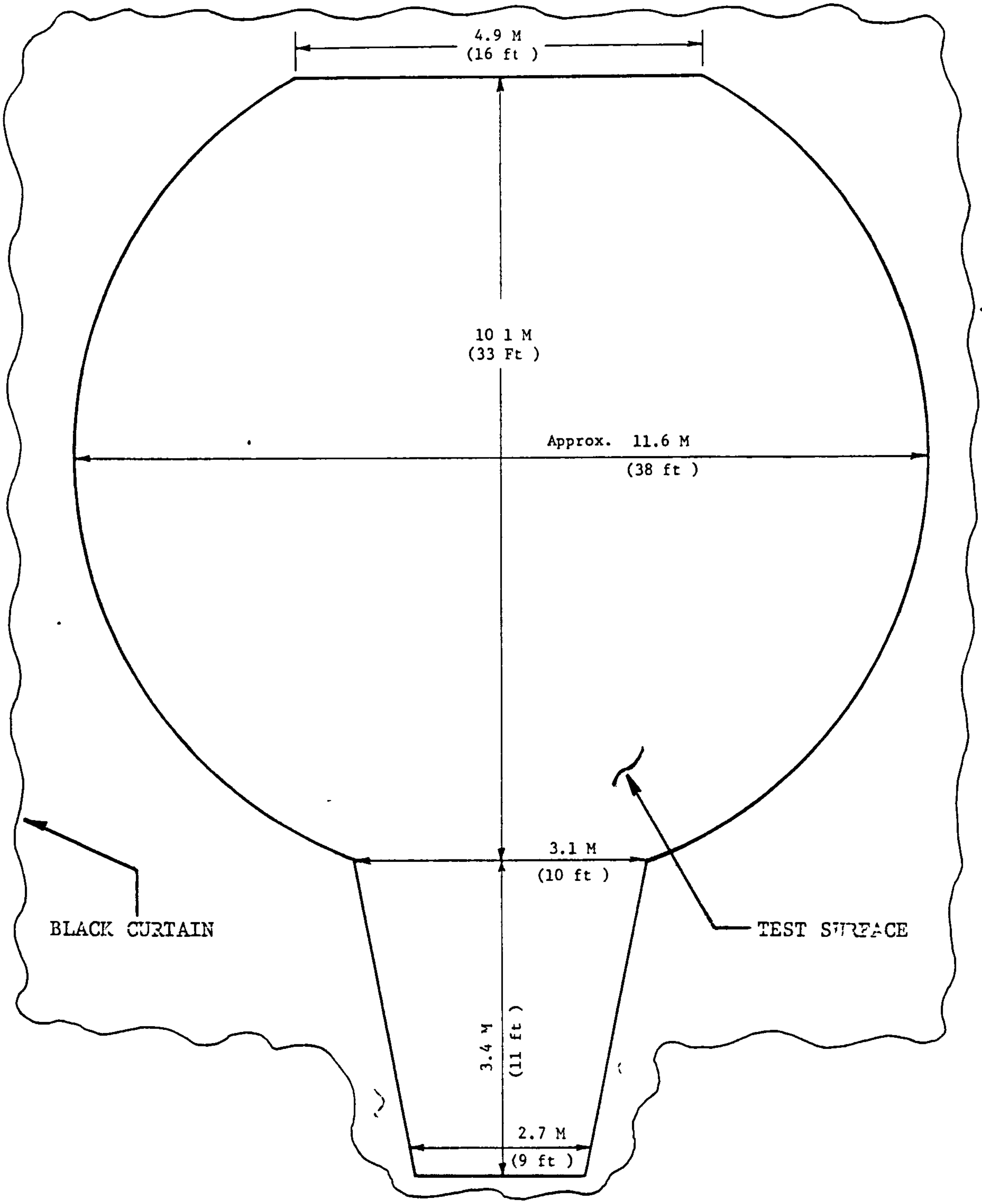

Figure 2-7: Teleoperation and Robotics Facility Air Bearing Test Area

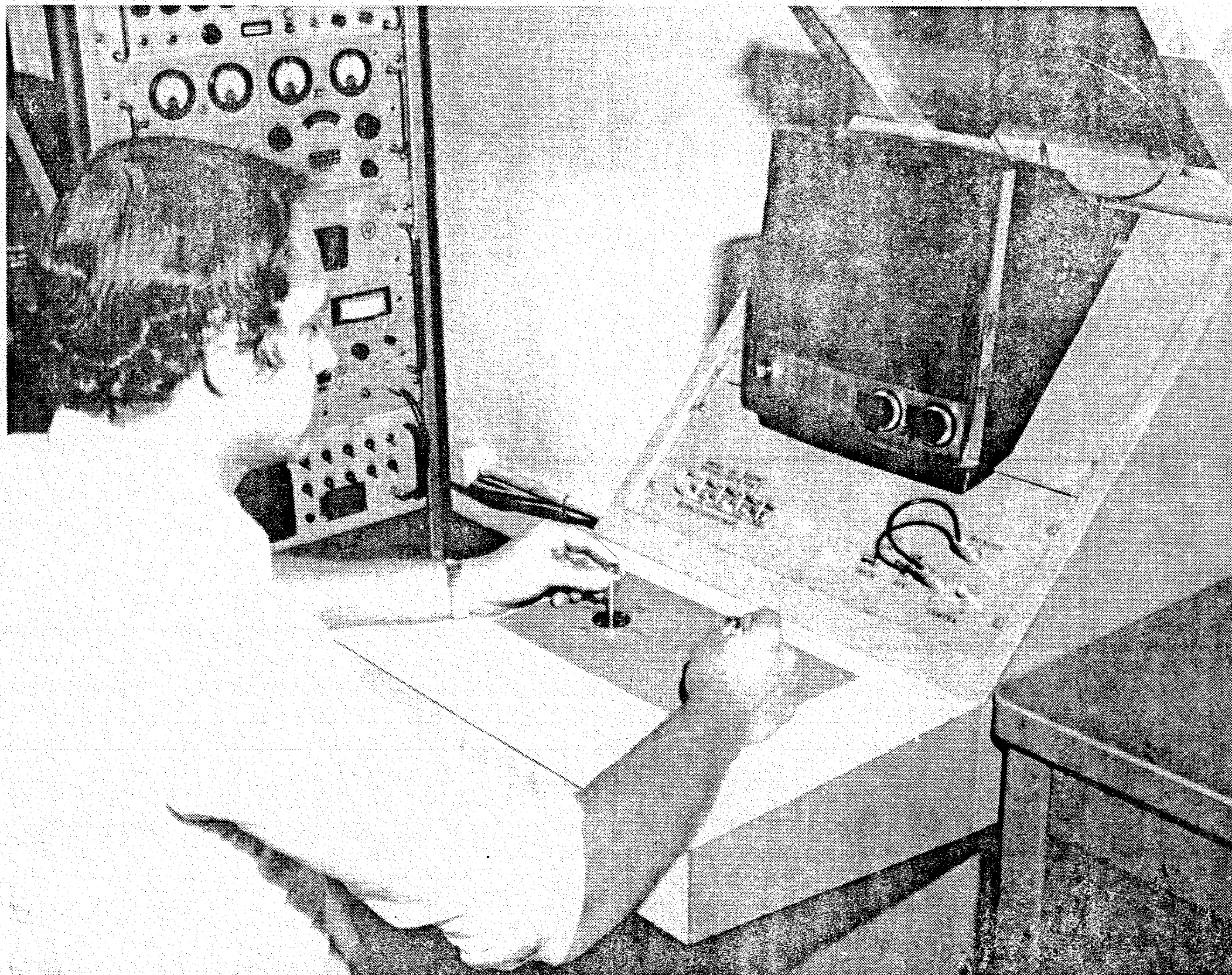

Figure 2-8: Teleoperation and Robotics Laboratory
Operator's Control Station

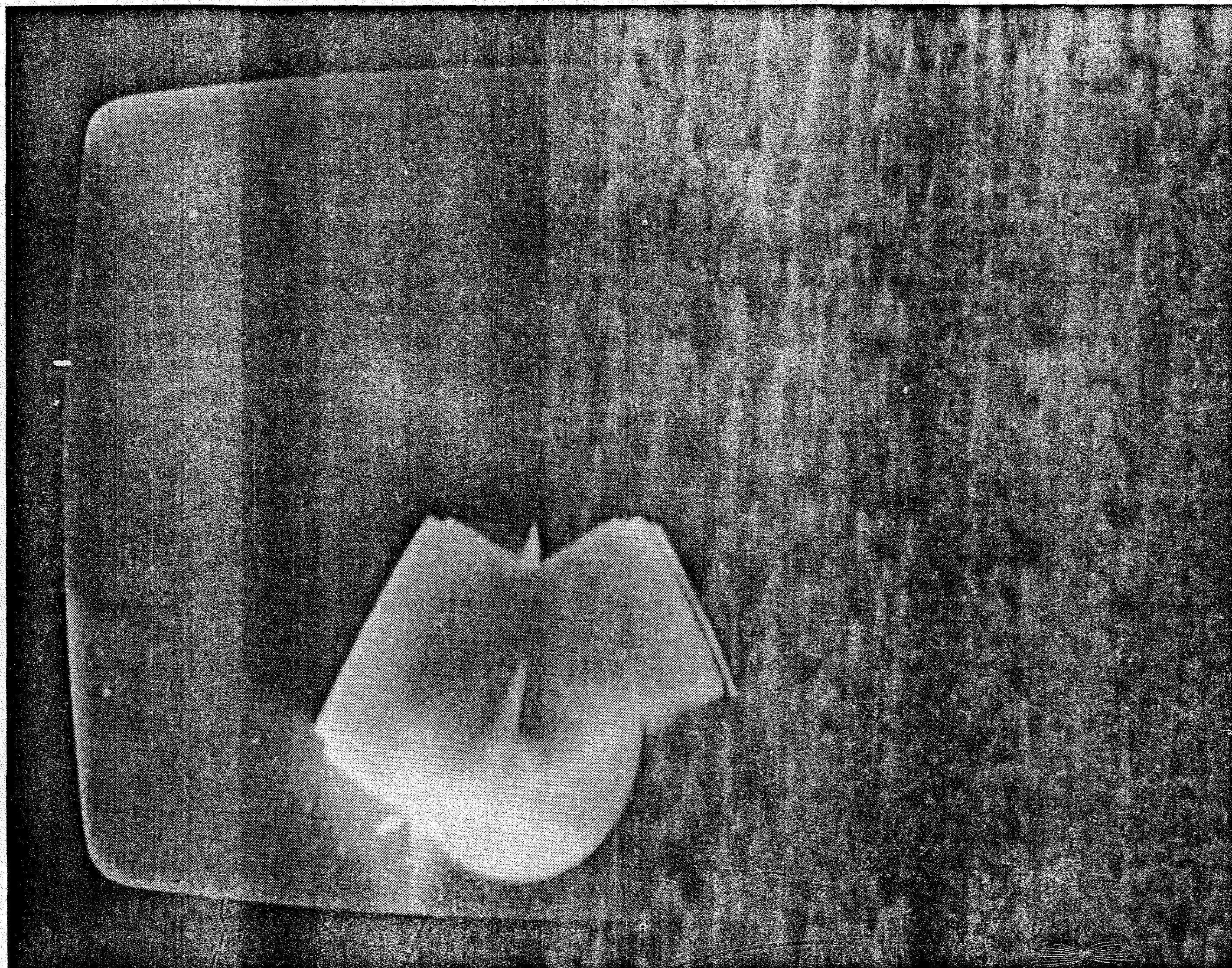

Figure 2-9: MMS to Teleoperator Distance of 8.5 m (28 ft.), Showing Effects of Solar Illumination on Video Feedback. Lack of video feedback resolution is noted when compared to MMS inset in upper right.

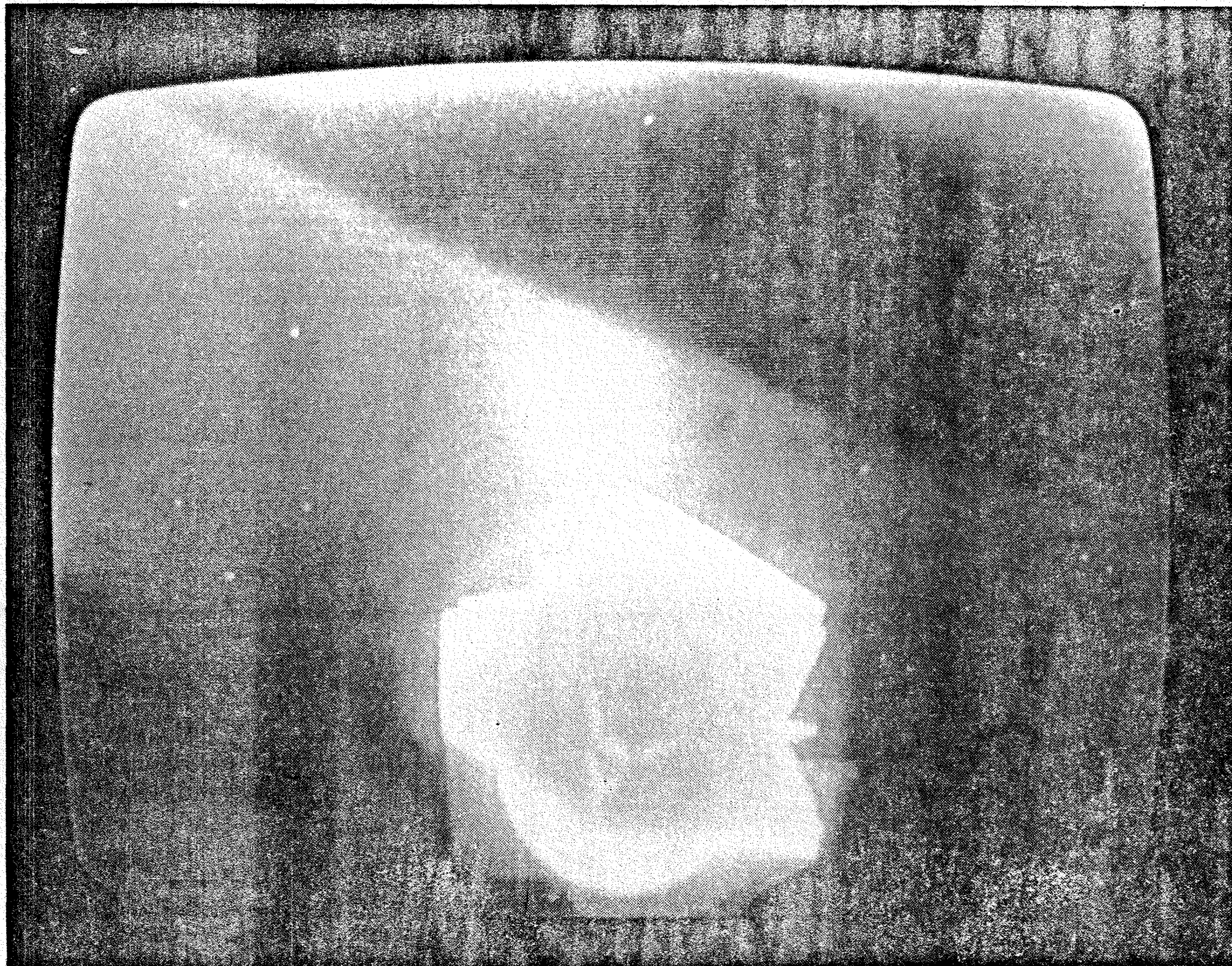

Figure 2-10: MMS to Teleoperator Distance of 8.5 m (28 ft.), Solar Illumination in Combination with Single, Top Mounted On-Board Flood Light. Note equipment modules are now illuminated.

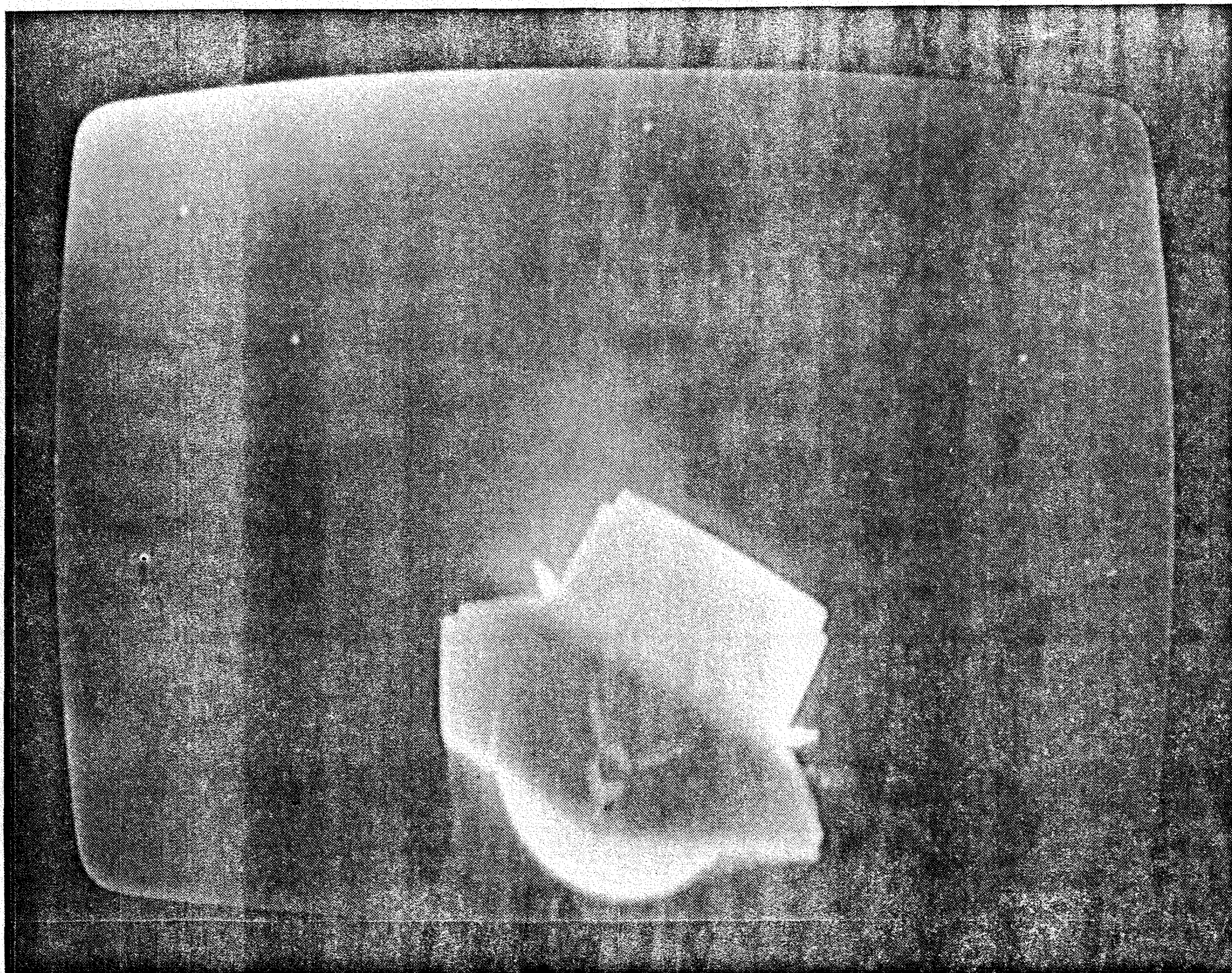

Figure 2-11: MMS to Teleoperator Distance of 8.5 m (28 ft.) with Solar Illumination Plus Two On-Board Flood Lights. The dark band through the center of the MMS is the result of raster retrace.

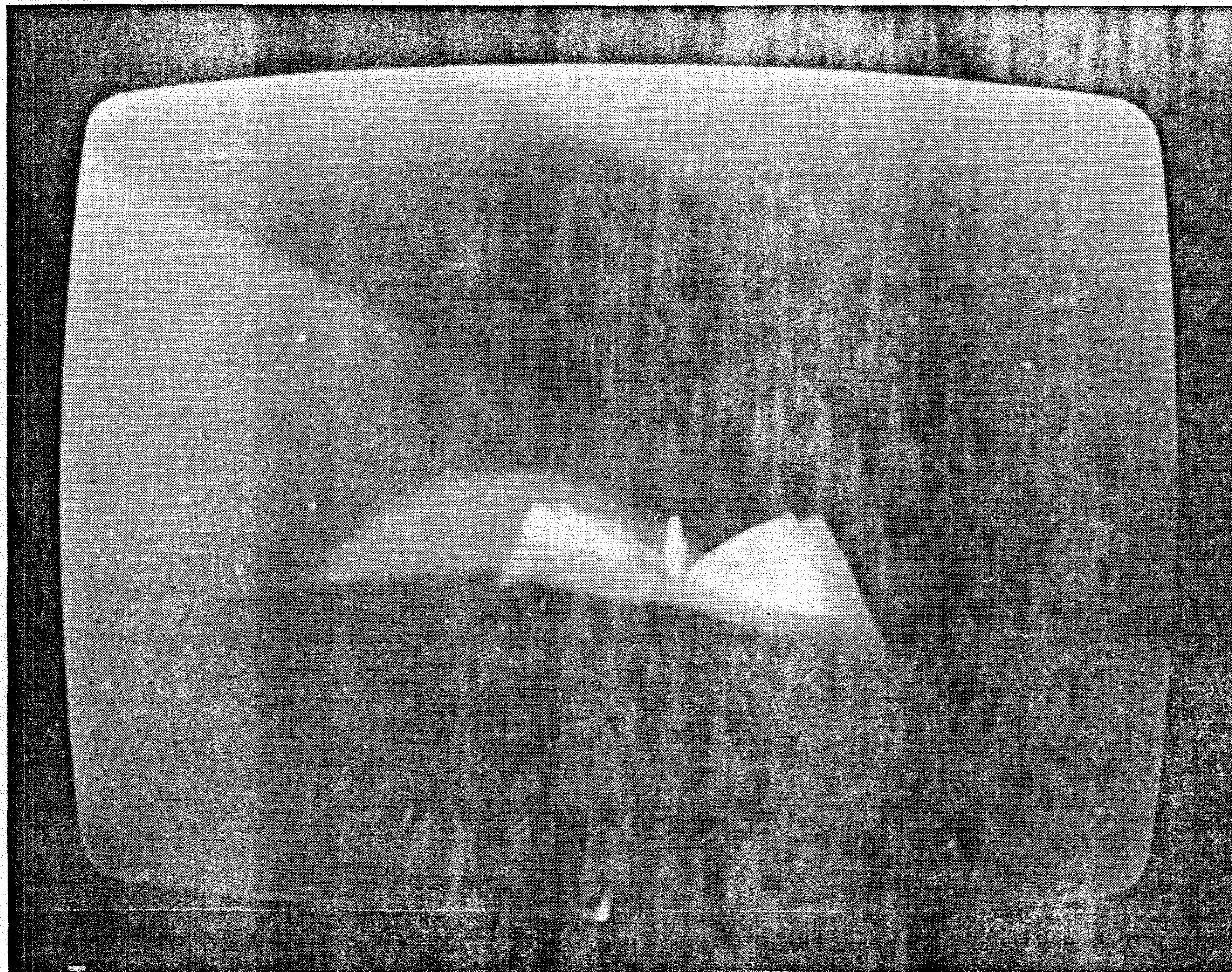

Figure 2-12: MMS to Teleoperator Distance of 7.62 m (25 ft.) Showing Solar Illumination and Effects of Teleoperator Shadowing on Target. Sun is coming from behind teleoperator.

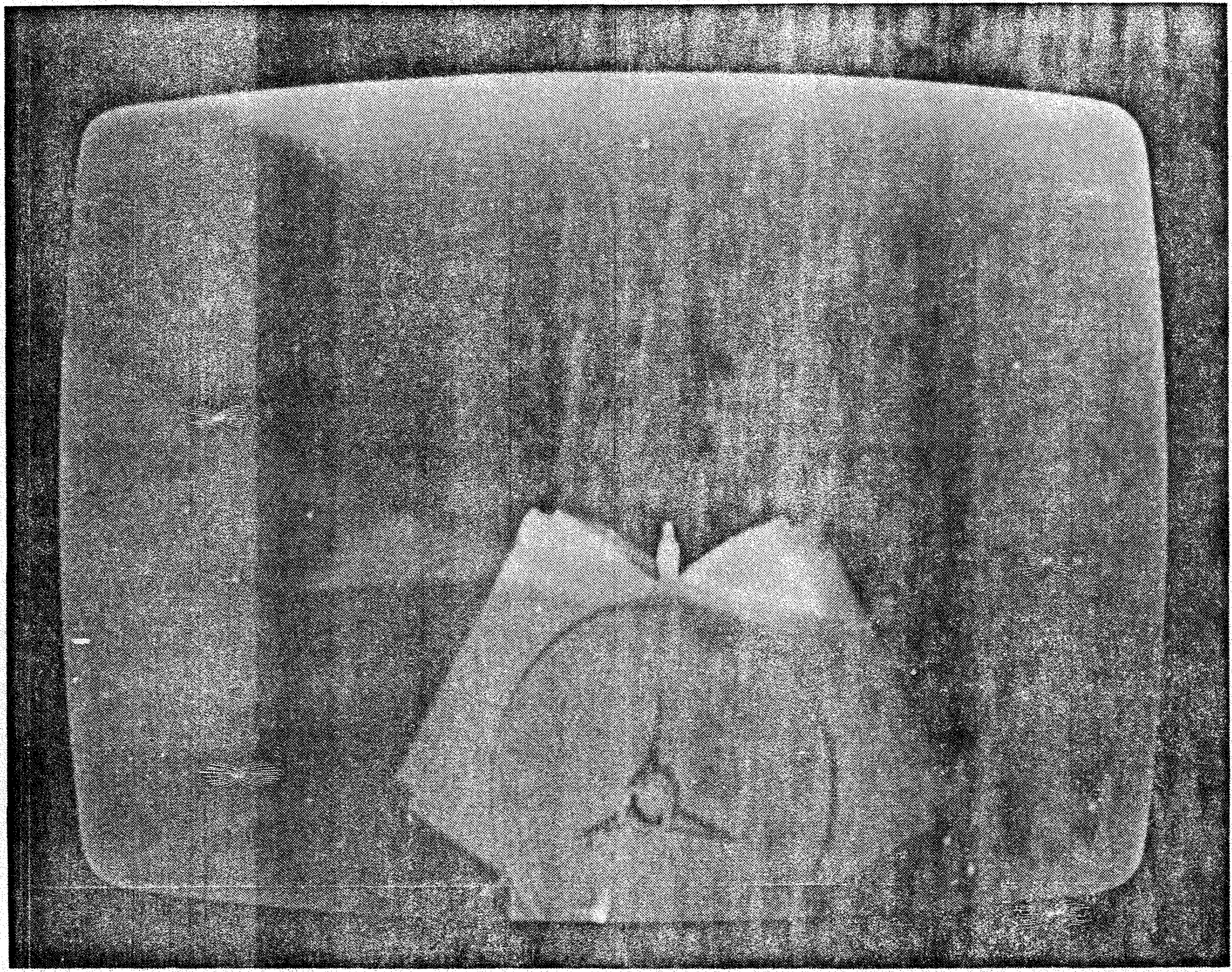

Figure 2-13: MMS to Teleoperator Distance of 7.62 m (25 ft.). Solar illumination from behind teleoperator mockup, showing effects of a single on-board left mounted flood light. Note illumination of HGA and equipment modules as compared to Figure 2-12.

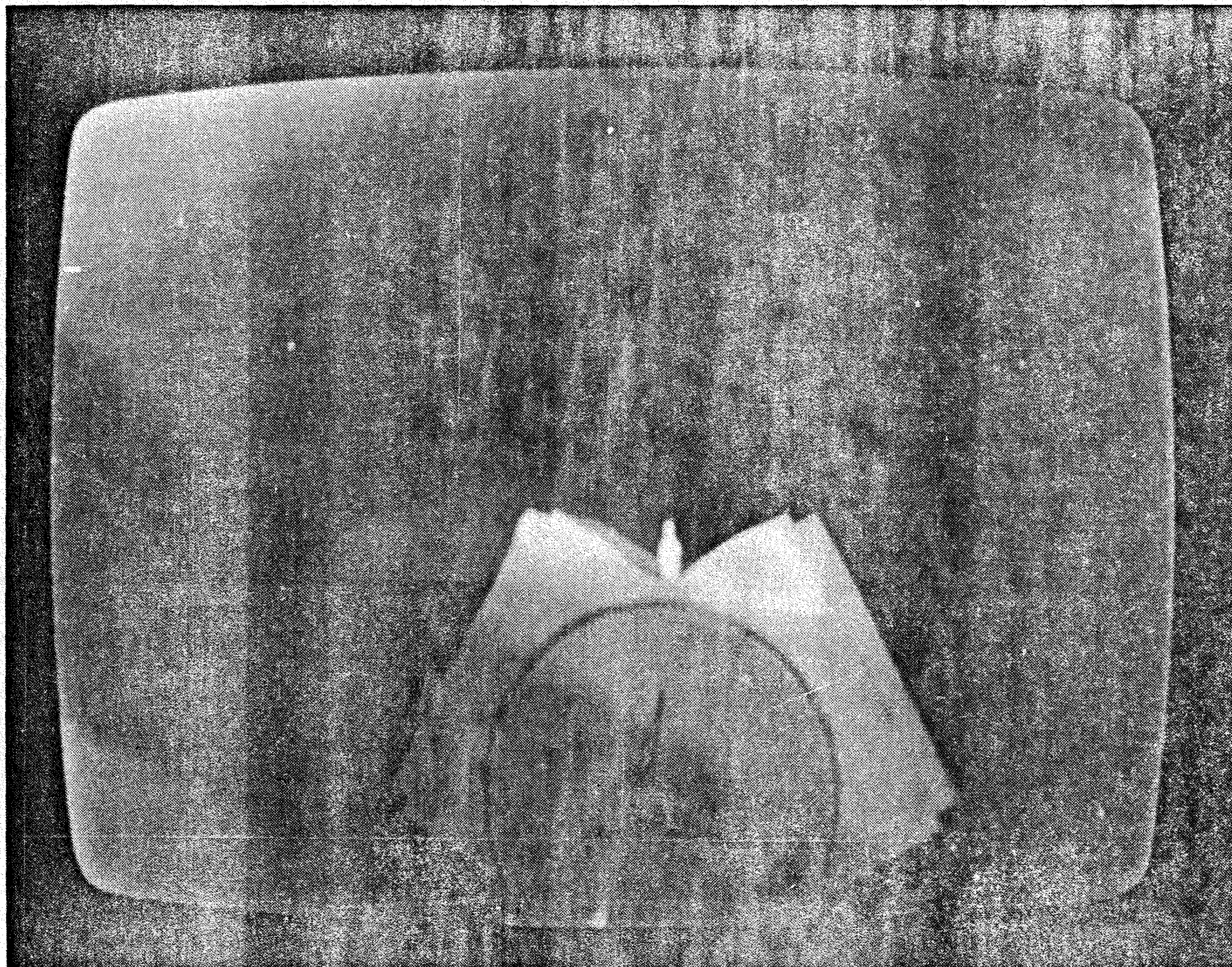

Figure 2-14: MMS to Teleoperator Distance of 7.62 m (25 ft.), with Solar Illumination Coming from Behind Teleoperator, Showing Effects of Both Left and Right Mounted On-Board Flood Lights

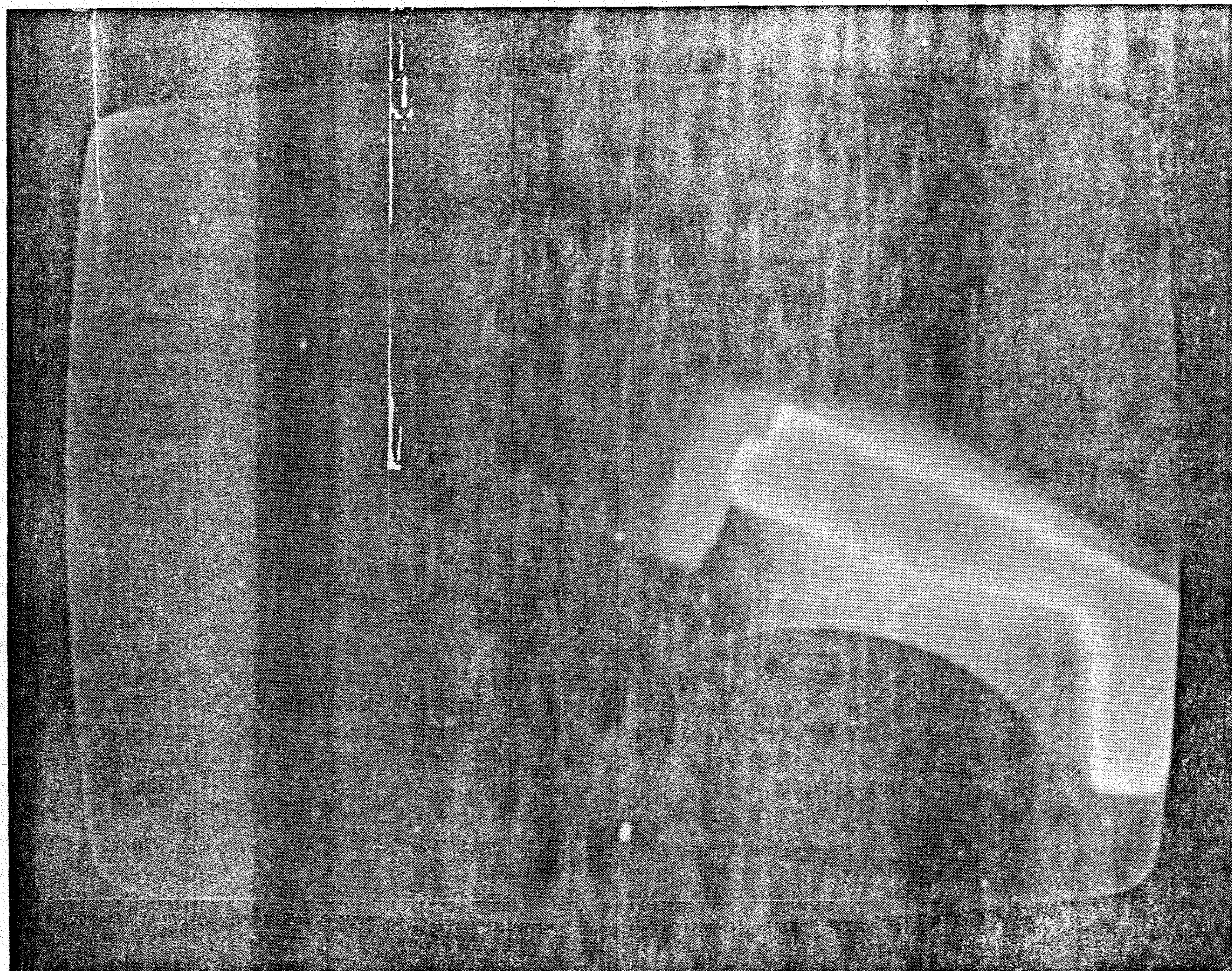

Figure 2-15: MMS to Teleoperator Distance of 5.2 m (17 ft.), Showing Solar Illumination Coming from Above and Behind Teleoperator. Note image blooming on video feedback as a function of illumination intensity. Illumination at 10,000 foot candles coupled with auto iris on the camera characteristically resulted in this type of display.

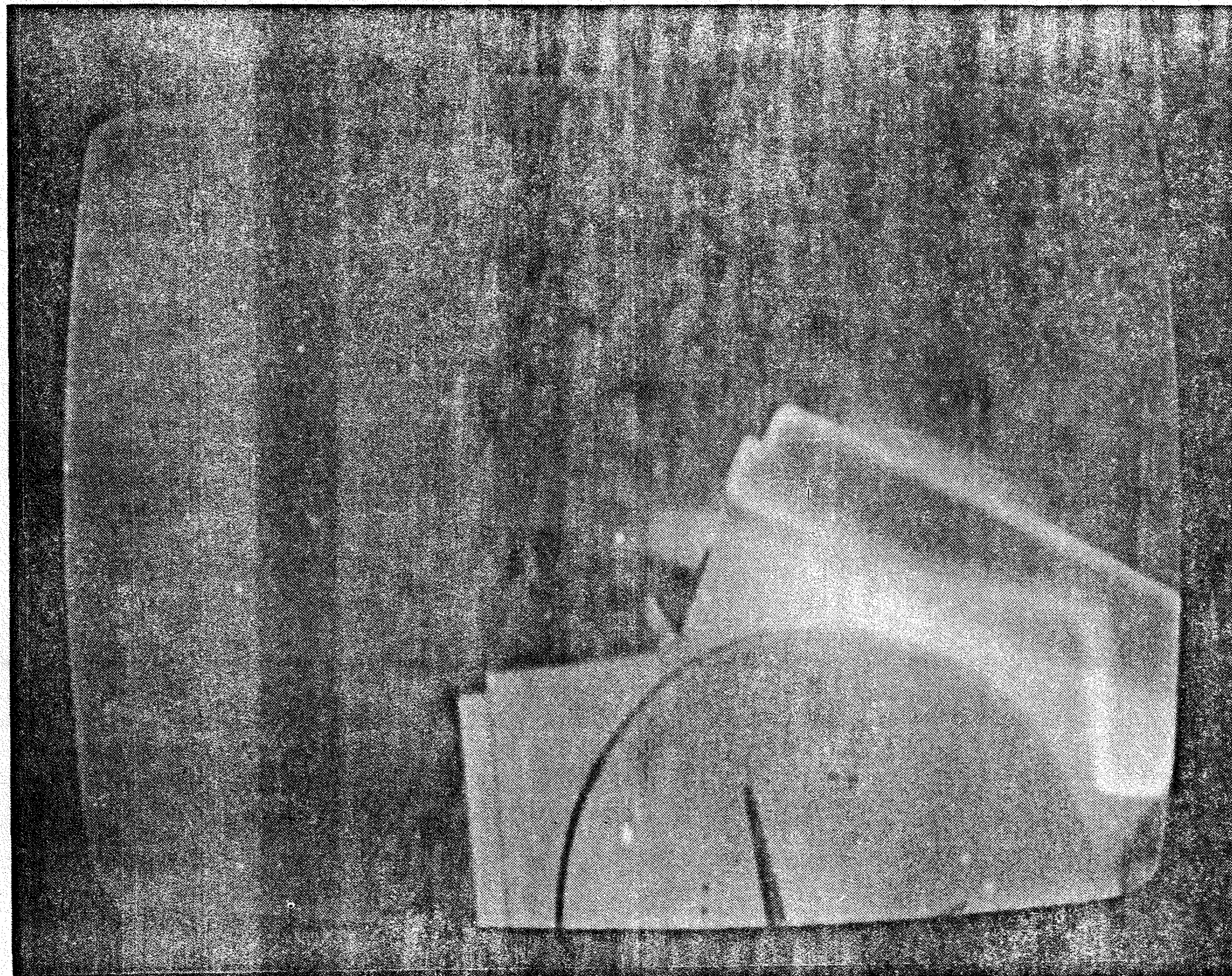

Figure 2-16: MMS to Teleoperator Distance of 5.2 m (17 ft.) with Solar Illumination Coming from the Same Position as in Figure 2-15. However, this figure shows the effect of a single right mounted on-board flood light which is capable of illuminating the HGA.

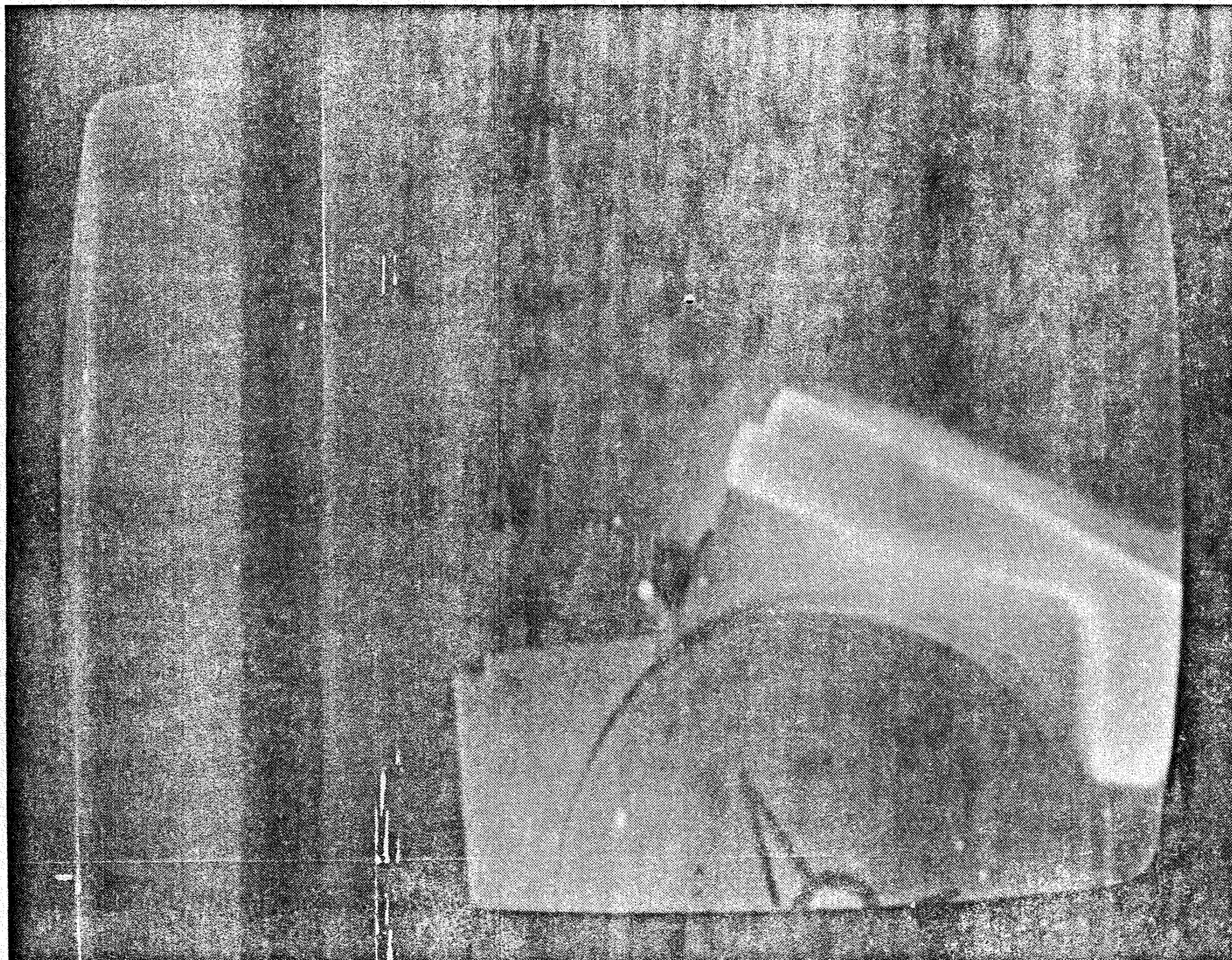

Figure 2-17: MMS to Teleoperator Distance of 5.2 m (17 ft.), Showing Effect of a Left Mounted On-Board Flood Light Overcoming Solar Illumination and Aiding in Video System Resolution of the HGA and Docking Probes

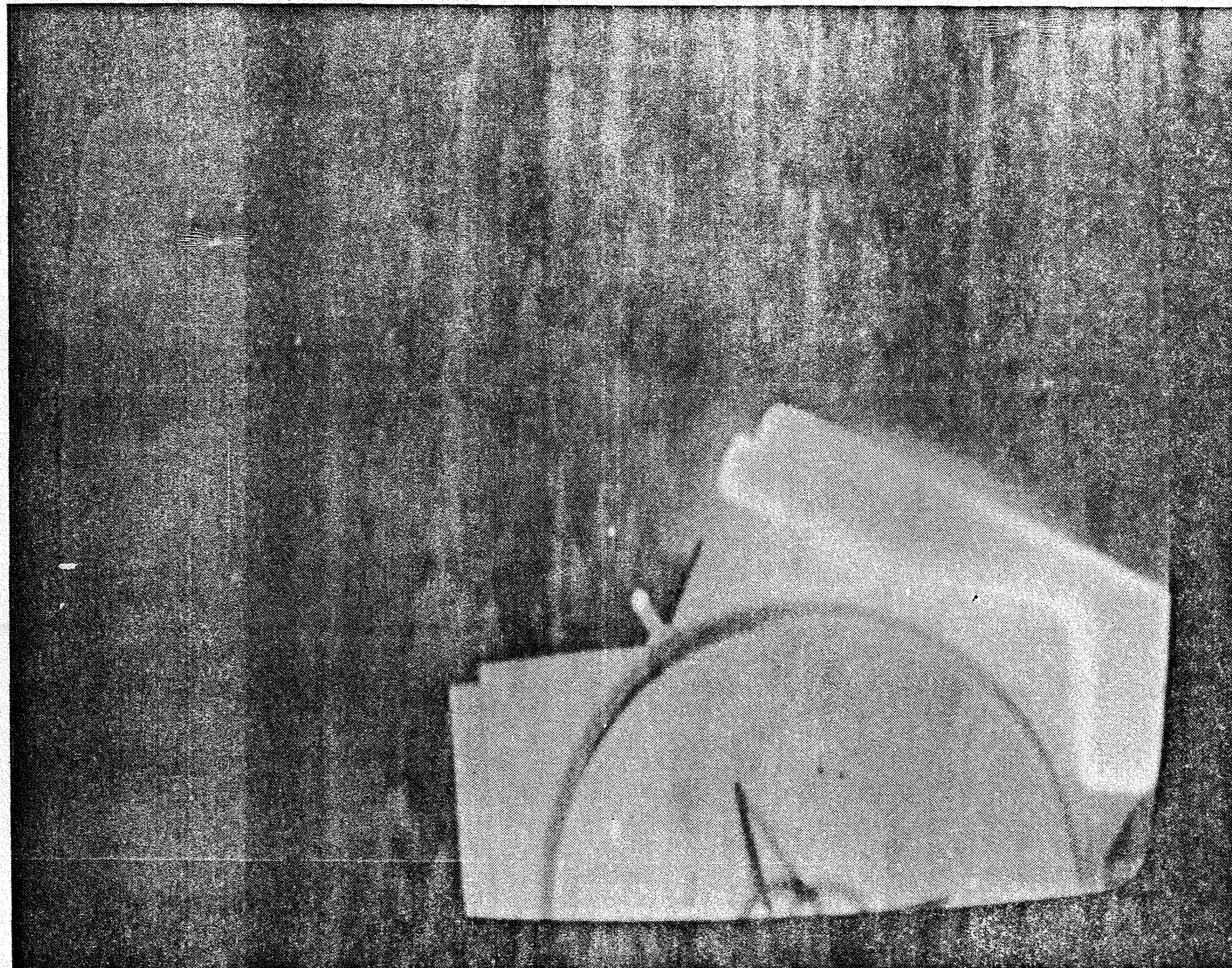

Figure 2-18: MMS to Teleoperator Distance of 5.2 m (17 ft.), Showing the Effects of Both Left and Right On-Board Flood Lights Illuminating the MMS Target, Especially the Docking Probes at Far Right and Top Left. Note video blooming is still apparent on upper equipment module.

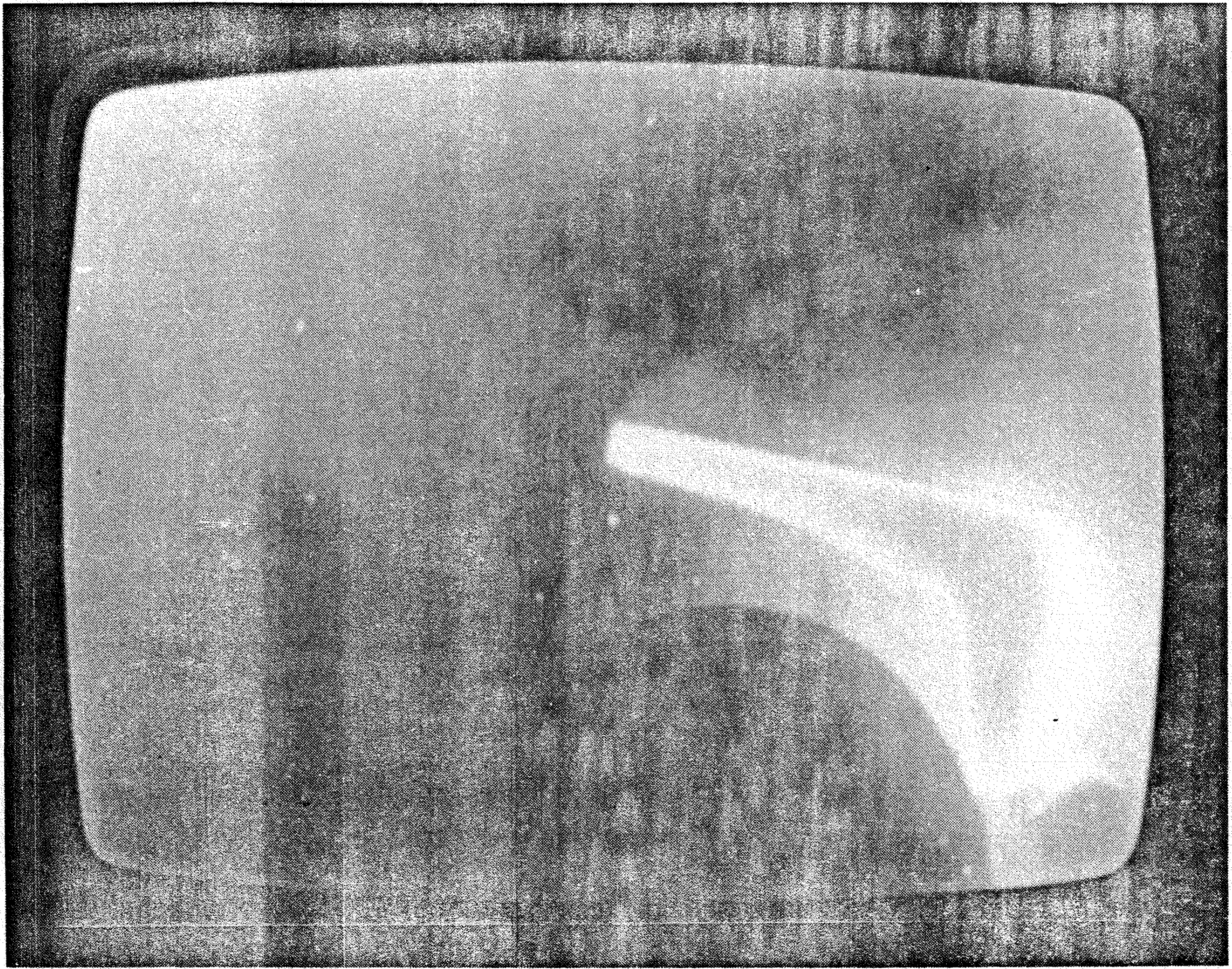

Figure 2-19: MMS to Teleoperator Distance of 5.2 m (17 ft.), Showing Illumination by Solar Simulator from a 40° Elevation and from Behind the Teleoperator Mockup. Note lack of resolution for the HGA and the docking probes.

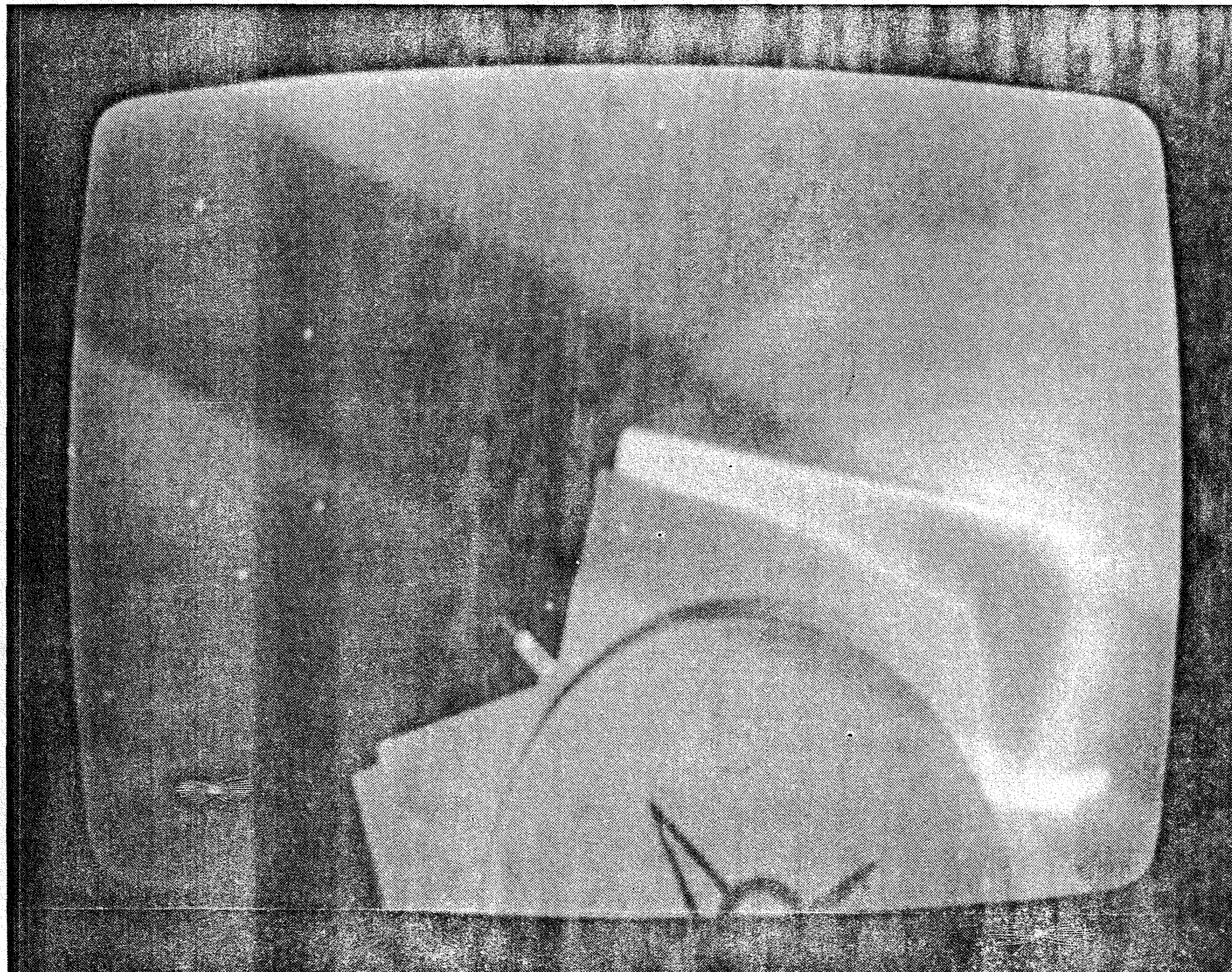

Figure 2-20: MMS to Teleoperator Distance of 5.2 m (17 ft.) with Solar Illumination Above (40°) and Behind the Teleoperator Mockup. This picture shows the resolution of spacecraft elements which can be produced by having a single teleoperator on-board flood light. Note HGA and docking probe resolution.

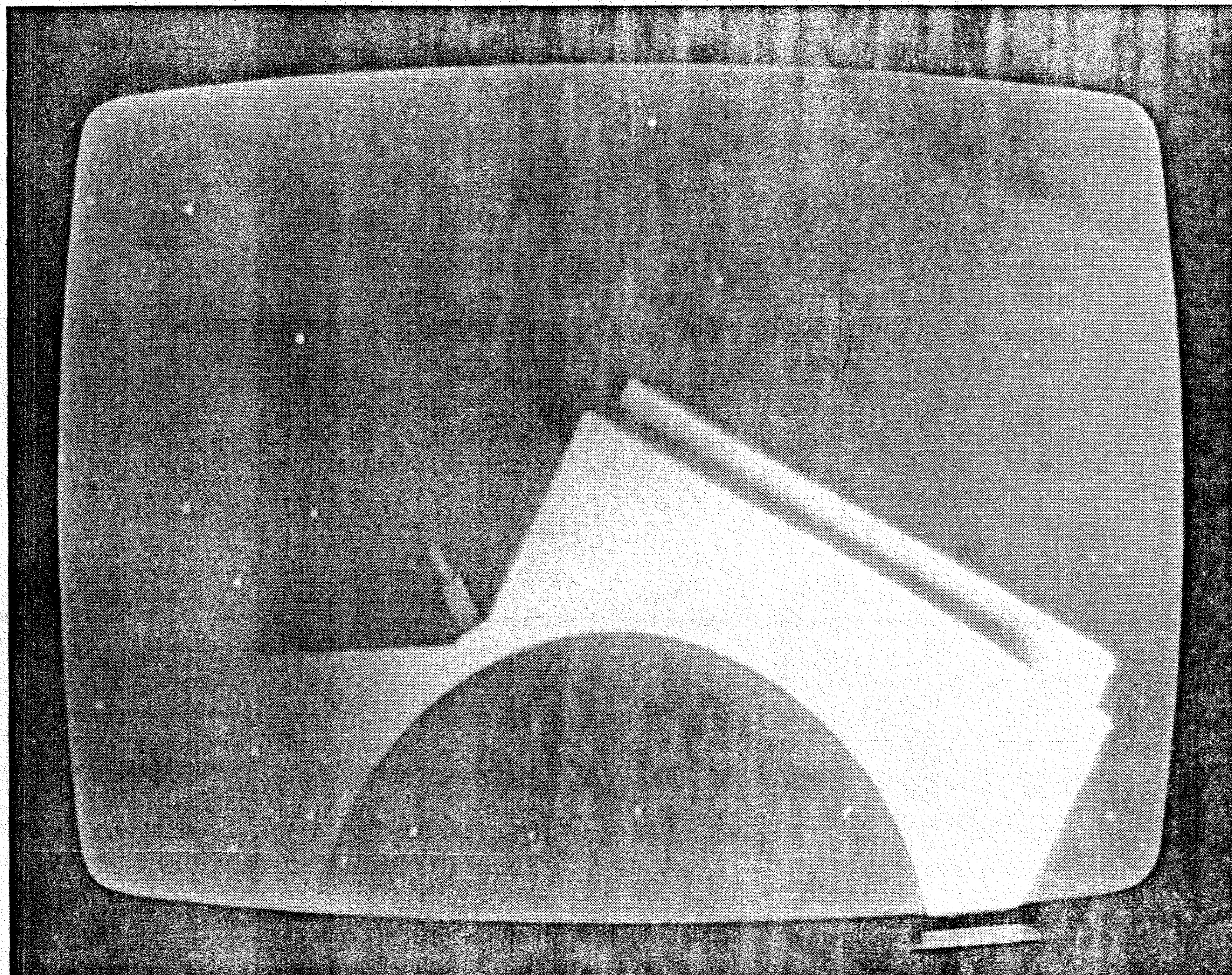

Figure 2-21: MMS to Teleoperator Distance of 3.05 m (10 ft.) with Solar Illumination Coming from Behind and the Right of the Teleoperator Mockup. Dark semi-circle is the HGA.

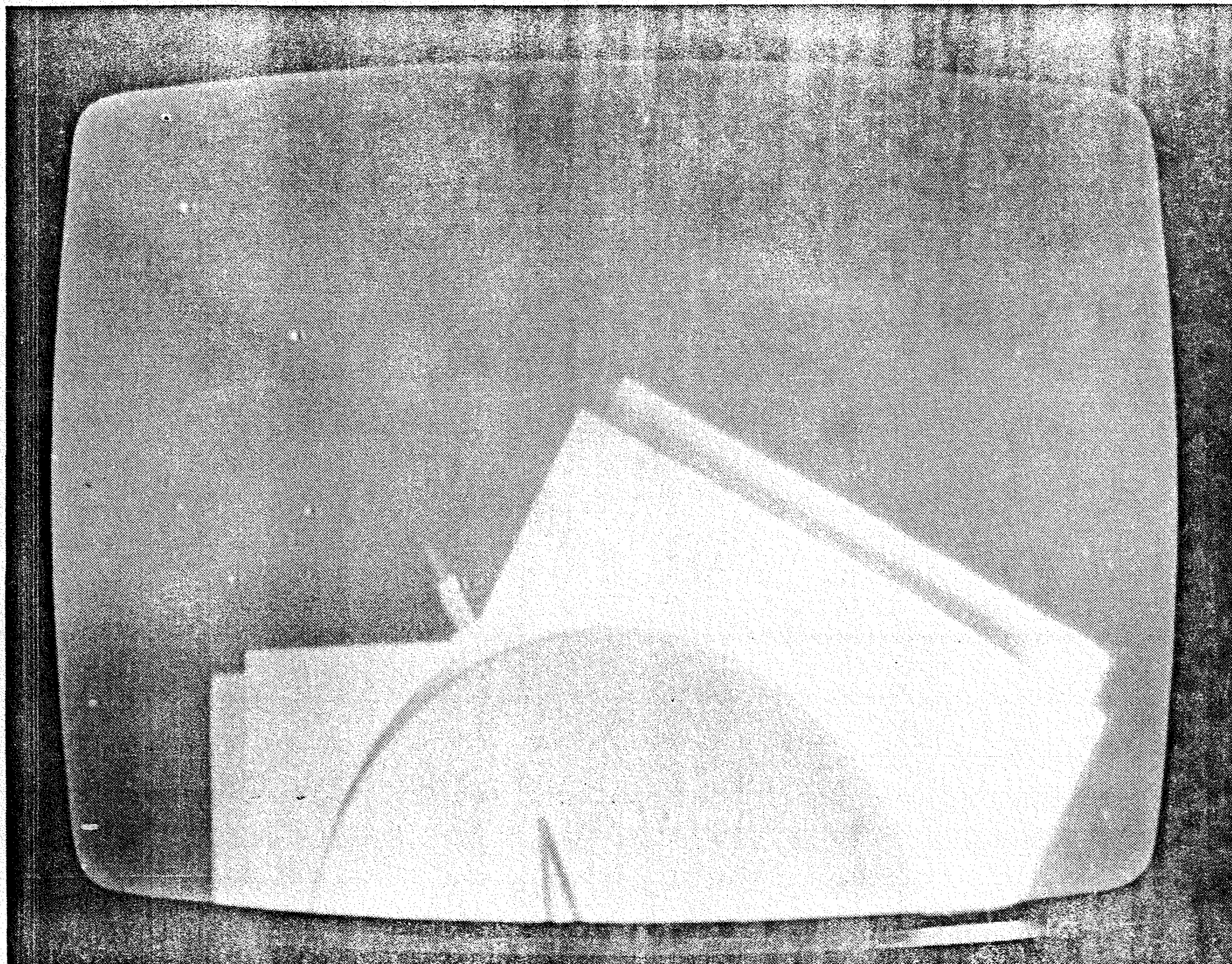

Figure 2-22: MMS to Teleoperator Distance of 3.05 m (10 ft.) with Solar Illumination Combined with a Single Right Mounted, On-Board Flood Light. Note resolution of docking probe and equipment at the left of the picture.

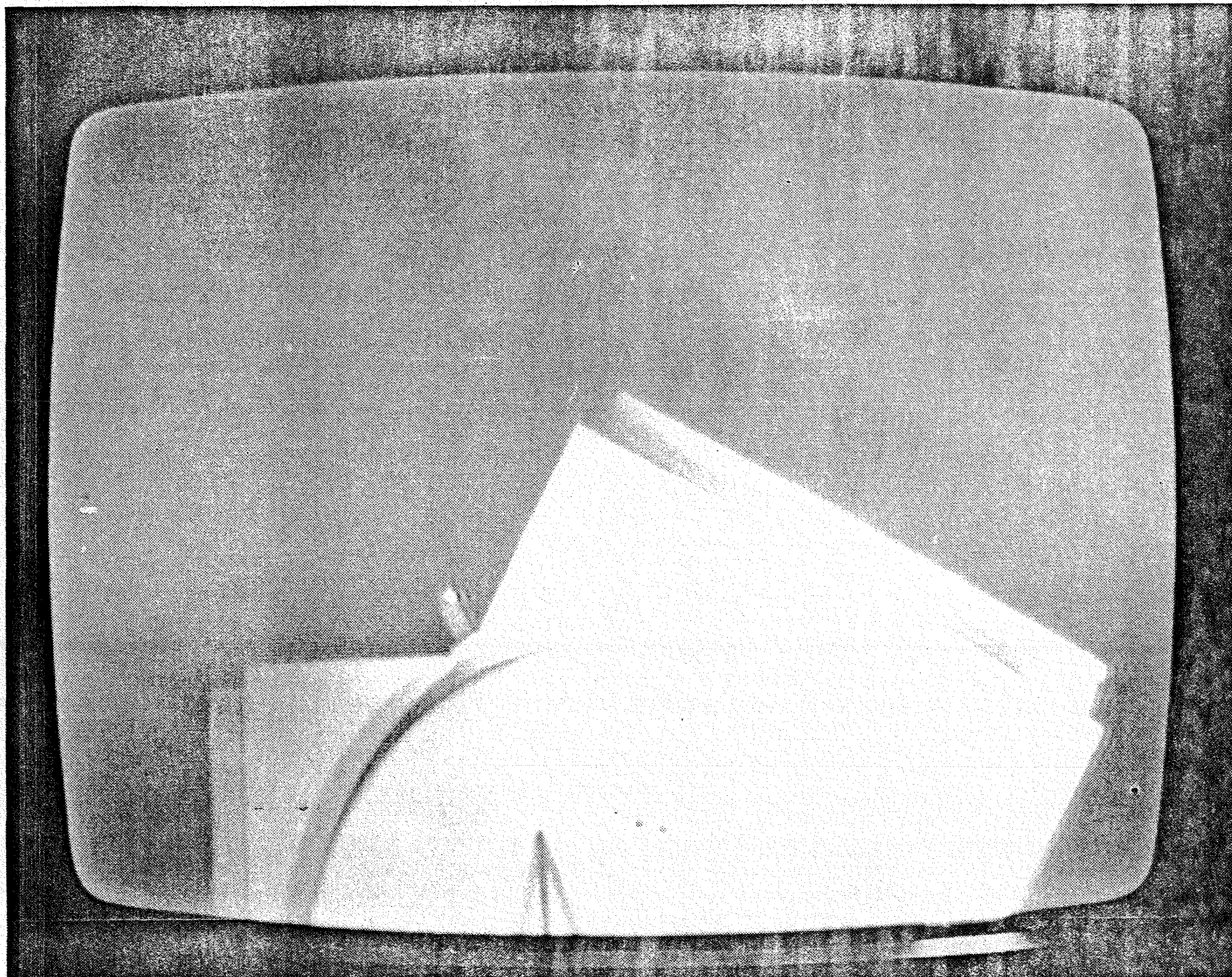

Figure 2-23: MMS to Teleoperator Distance of 3.05 m (10 ft.). In this figure, the image blooming noted at the right hand equipment module and HGA boundary is the result of solar illumination in combination with both the right and left mounted on-board flood lights. At a distance of 3.05 m, both on-board lights provide too much illumination for appropriate resolution.

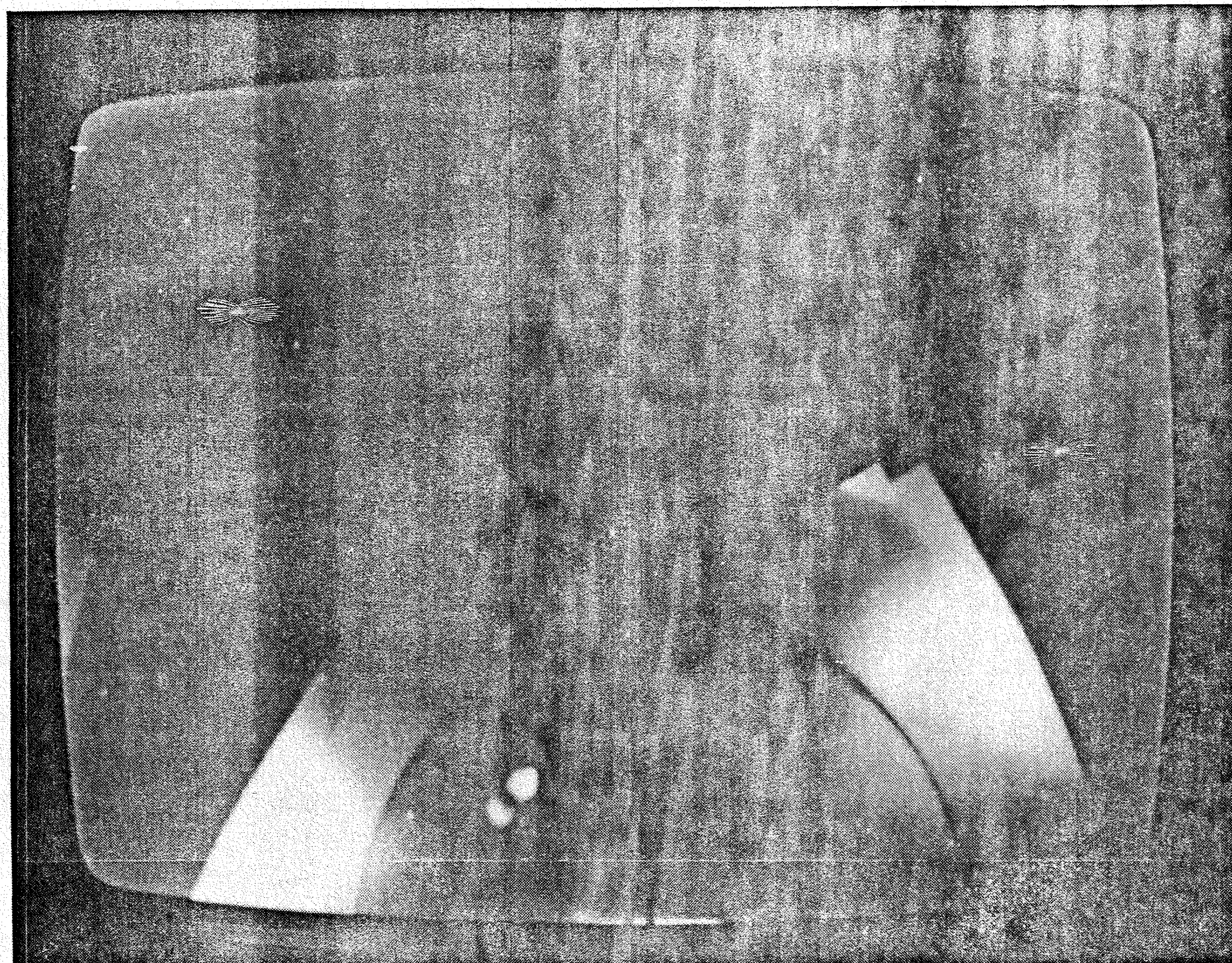

Figure 2-24: MMS to Teleoperator Distance of 2.1 m (7 ft.). Solar illumination is coming directly from behind the teleoperator mockup, with shadowing being broadcast by the teleoperator solar panels. No on-board lighting is provided in this figure.

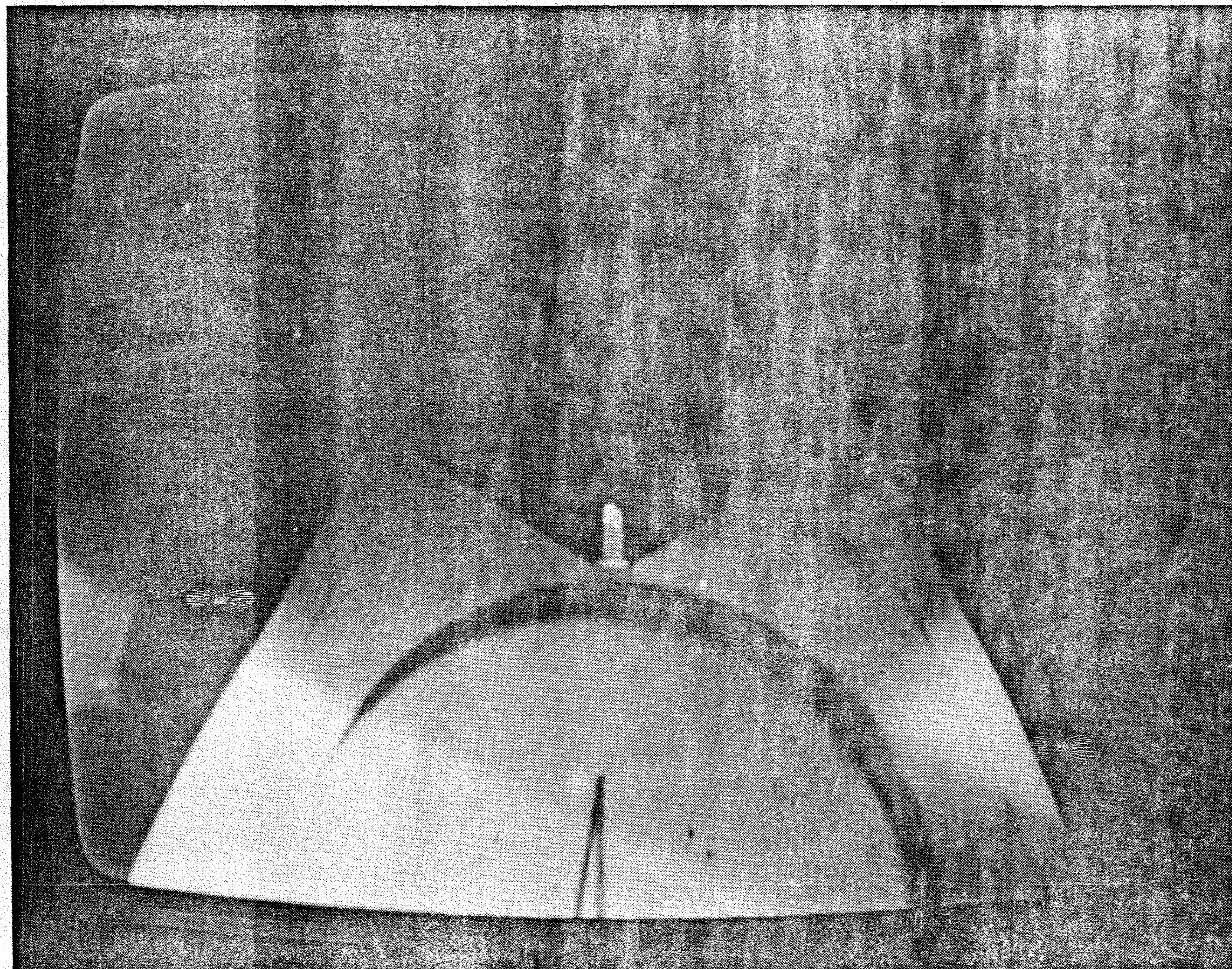

Figure 2-25: MMS to Teleoperator Distance of 2.1 m (7 ft.). Solar illumination is coming directly from behind the teleoperator mockup and the left mounted on-board flood light is on, illuminating the top docking probe.

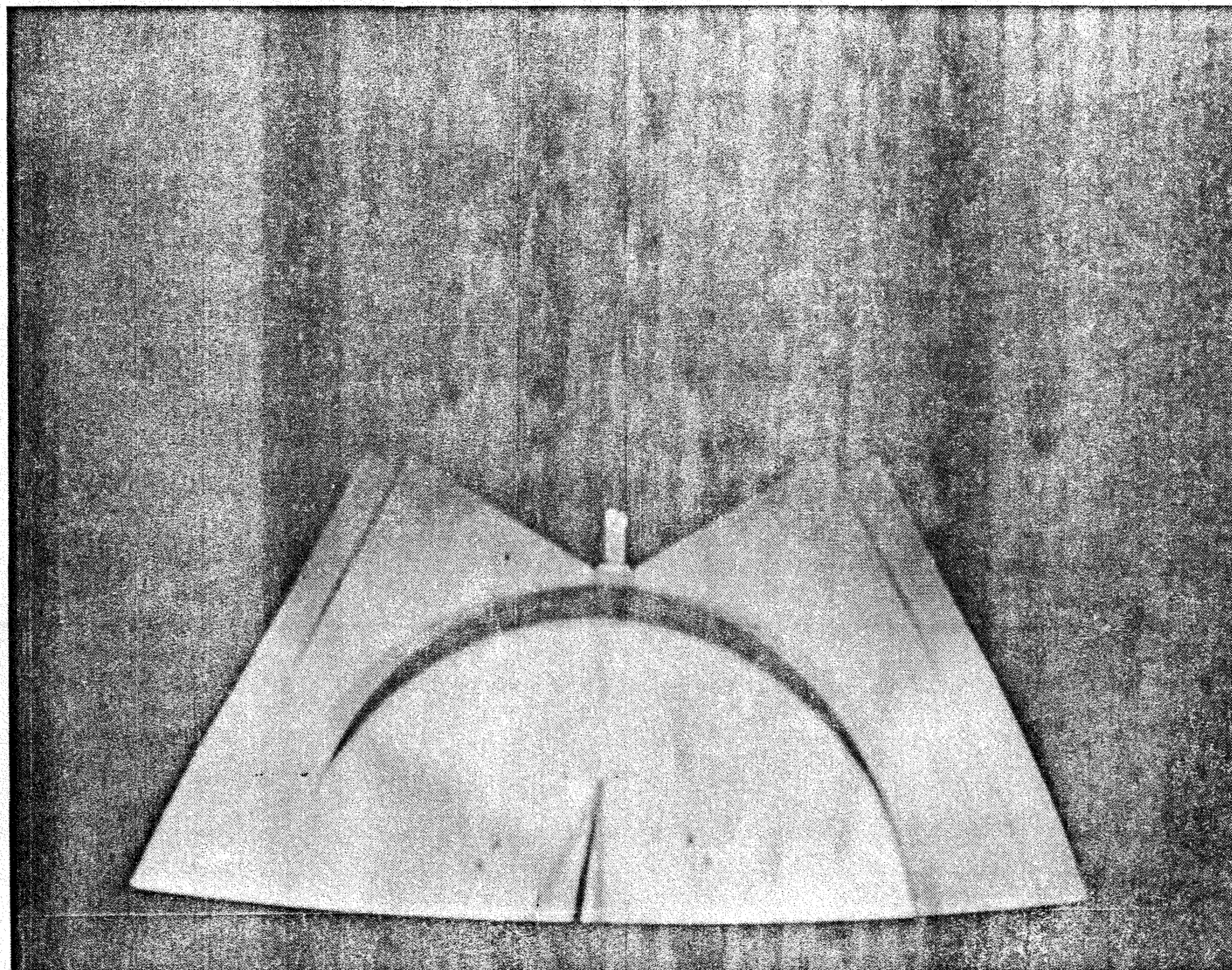

Figure 2-26: MMS to Teleoperator Distance of 2.1 m (7 ft.). Both the left and right mounted on-board flood lights illuminating the MMS target provide good contrast for the HGA boundary at the top of the target, but blooming at the left boundary.

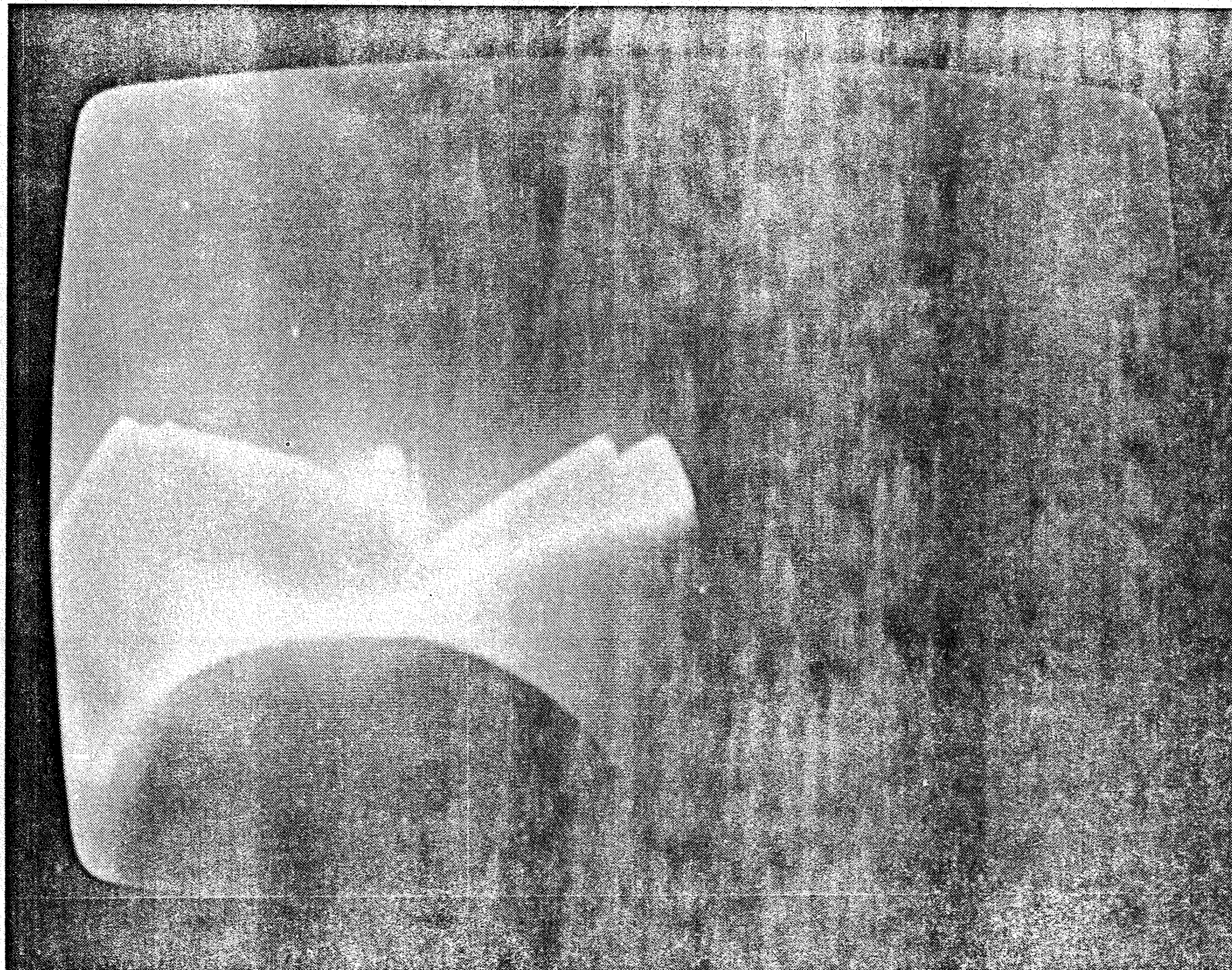

Figure 2-27: MMS to Teleoperator Distance of 2.1 m (7 ft.) as in Figures 2-24 through 2-26, but Solar Illumination Now Falls from the Upper Right, Causing Blooming and Deep Shadowing on the MMS Target.

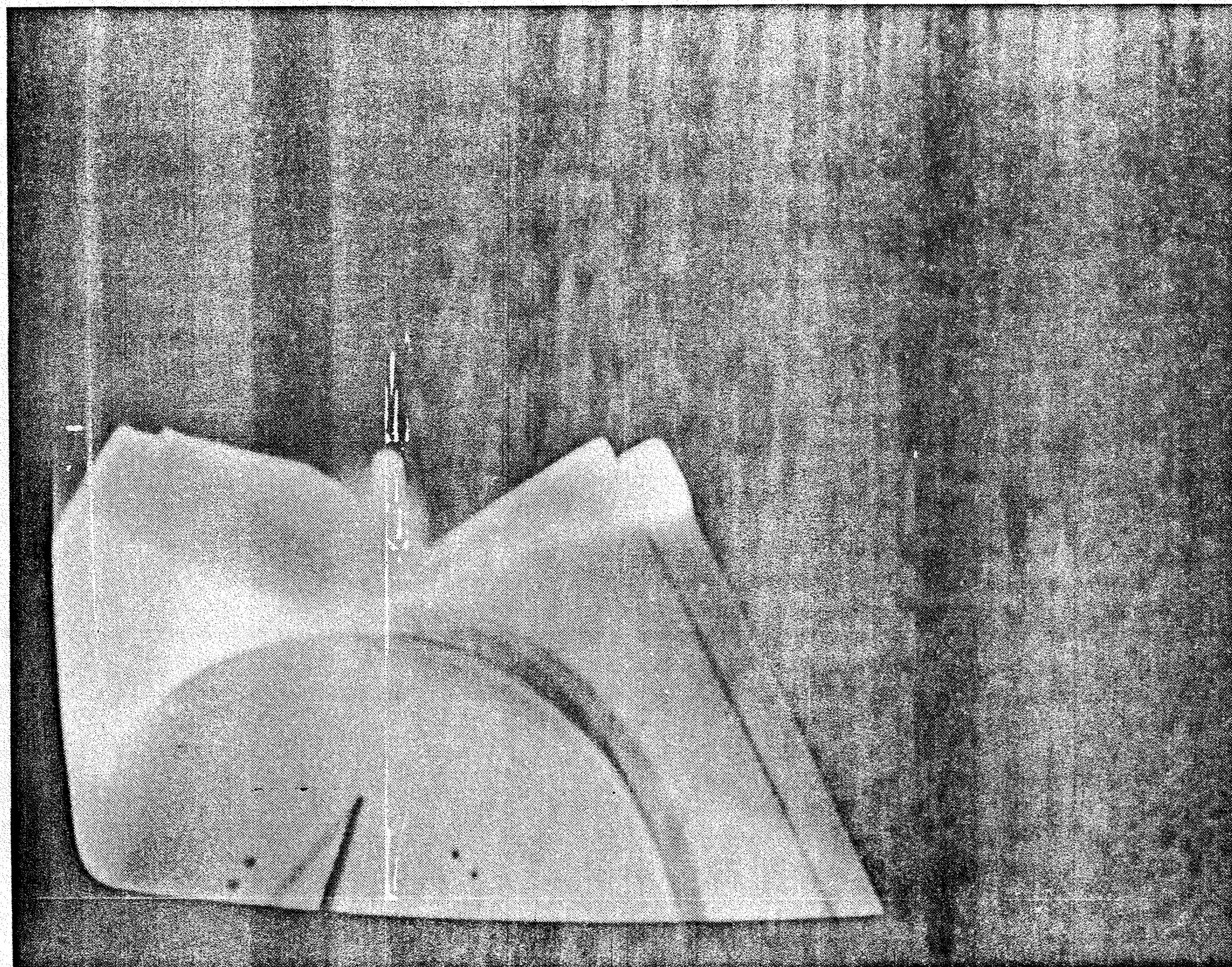

Figure 2-28: MMS to Teleoperator Distance of 2.1 m (7 ft.) with Solar Illumination Coming from the Upper Left. This figure shows the additional resolution available with a single right mounted on-board flood light. Note the good definition of the HGA boundary.

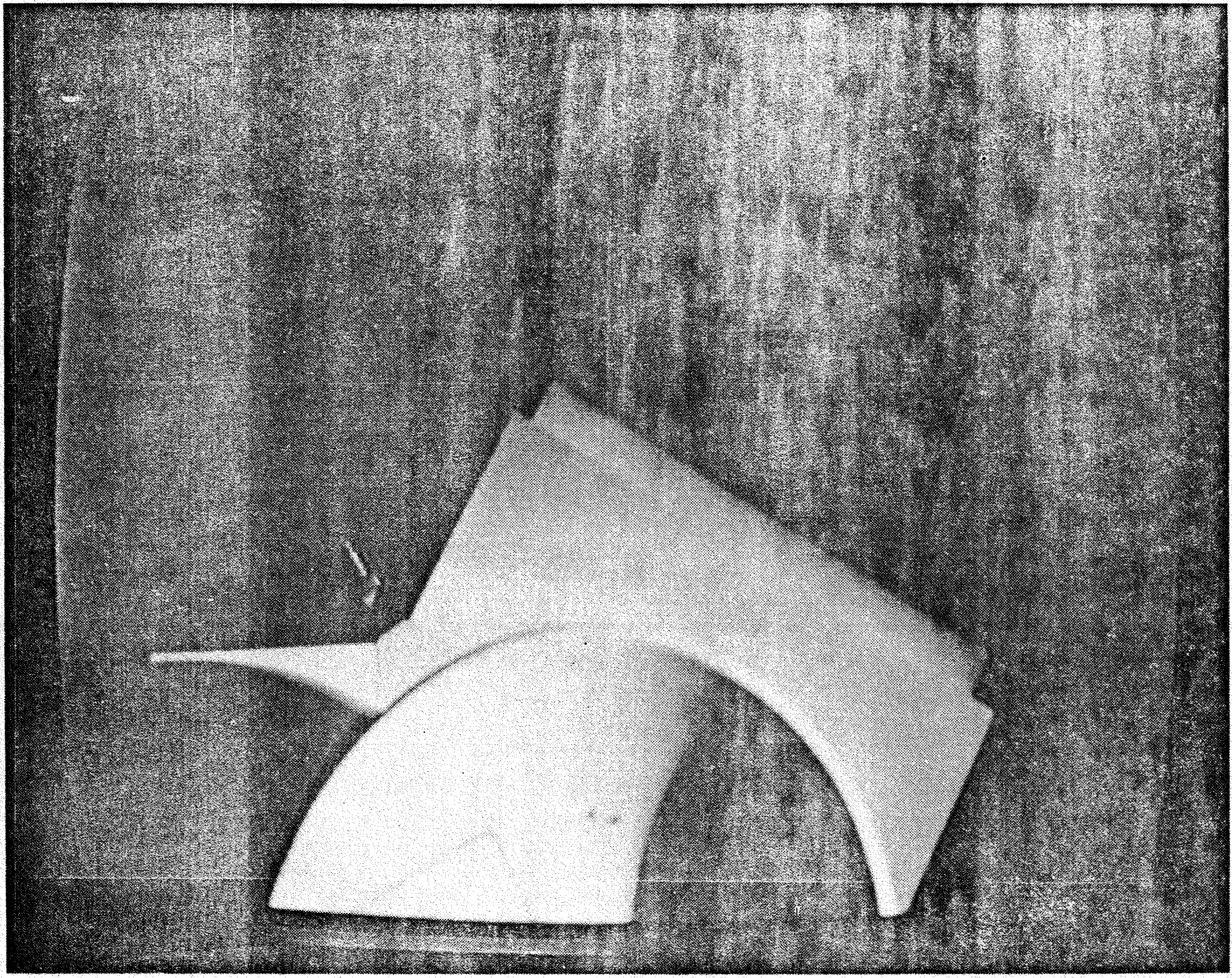

Figure 2-29: MMS to Teleoperator Distance of 2.1 m (7 ft.) with Solar Illumination Coming from the Far Right and No On-Board Lighting. This condition provides good contrasts but poor resolution of target elements not illuminated by the sun simulator.

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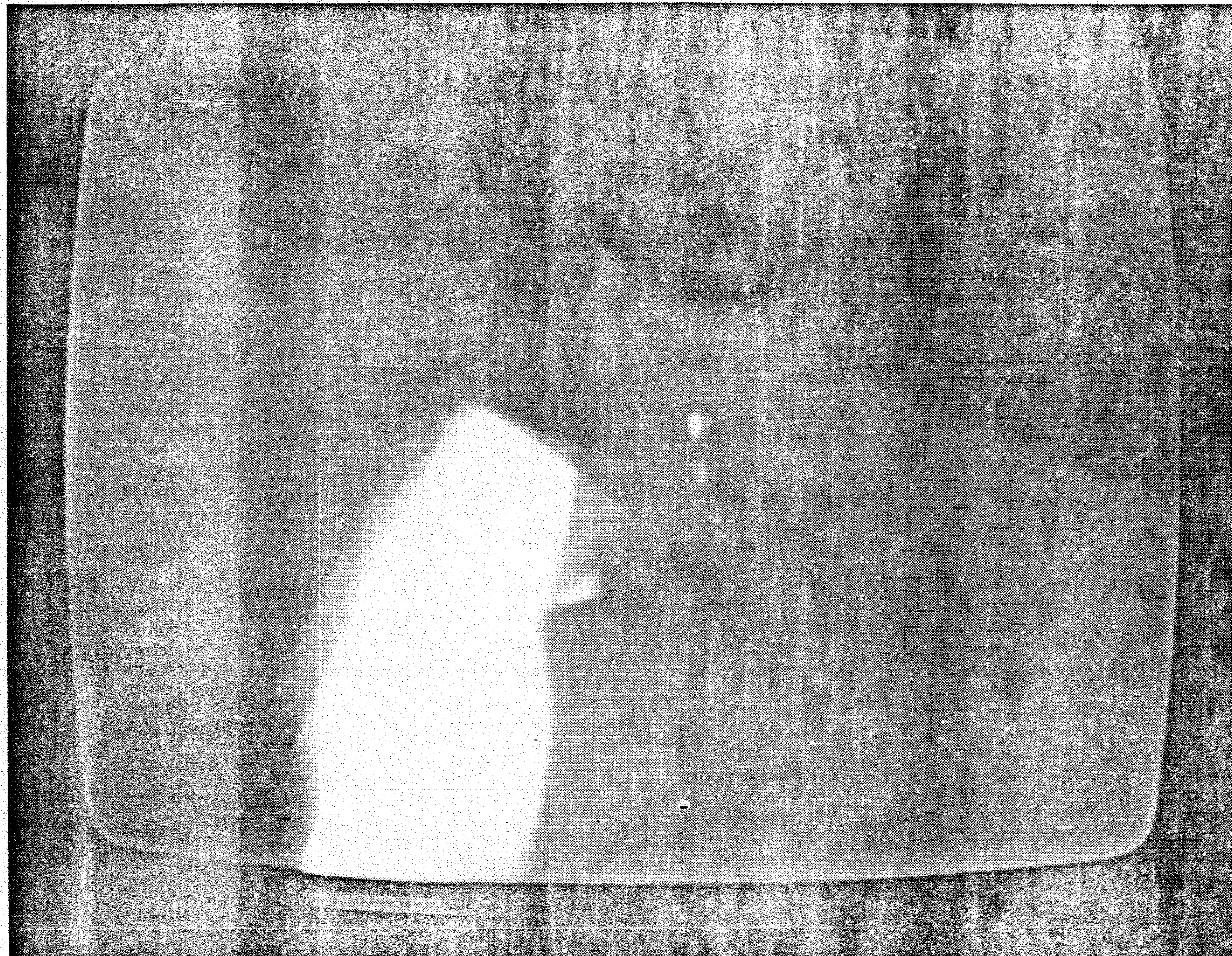

Figure 2-30: MMS to Teleoperator Distance of 1.52 m (5 ft.) with Approach Alignment Offset to the Left by 15°. Solar illumination source is also coming from the left and no on-board lighting is used. This combination of circumstances has resulted in an almost total loss of resolved visual information and represents a "worst case" effect of approach geometry and high intensity solar illumination.

specified lighting and viewing parameters, and each photograph is captioned with the specific levels of these parameters related to the photo. A complete set of photographs and accompanying descriptive literature was presented to the COR at the end of the test series.

2.1.3.3 Conclusions and Recommendations

The conclusions drawn from this initial evaluation can most appropriately be applied toward procedures and methods employed in future lighting studies. The primary objective in conducting the evaluation was to study the parameters that would impact future studies in which actual operations would be performed by test subjects. The photographs document that image "blooming," which occurs at the monitor on highly reflective, intensely lighted targets, makes target resolution very difficult for the operator. It is recommended that the operator be able to exercise manual control over the iris setting and control over target sensitivity of the video camera. An automatic iris resolves its setting by accounting for the average scene lighting. This means that small, highly reflective targets of interest in a black space environment are only a part of the data used for automatically setting an iris, but are most probably the object of operational interest in the camera field of vision. If the operator controls the amount of light coming through the iris, the video sensor can be stopped down so that the displayed feedback is not "bloomed out" by overexposure. This would allow better target definition on the display monitor and consequently provide more and better information to the human operator.

The photographs of the evaluation further show that on-board lighting is effective for close-in illumination of shapes and spaces hidden in deep shadow. It is recommended that a variety of lights which differ in illumination output, power consumption, spectral output, beam width, and the like, be investigated.

It can also be seen that the location of on-board lighting affects the illumination of spaces on the MMS. It is recommended that as well as studying specific fixed locations for on-board lights, it might be advantageous to investigate the potential for a movable light platform with pan, tilt, and extension capabilities for the TRS.

2.2 REMOTE APPROACH AND DOCKING STUDY

Many of the missions proposed for the Teleoperator Maneuvering System (TMS) involve approach and docking of the TMS to an orbiting spacecraft. Considerations of thruster power, thruster pulse cycles, on-board lighting, approach geometries, docking systems, camera positions, and ranging aids are currently being studied in the MSFC five degree-of-freedom (5 DOF) laboratory.

2.2.1 Objectives

This study was undertaken to evaluate human operator performance under selected levels of approach and docking conditions.

2.2.2 Procedures

The major equipment elements employed in this study were the 5 DOF air bearing mobility unit (MU) outfitted with the three-armed capture device, and the MMS mockup. The MMS mockup is described in detail in Paragraph 2.1.2, and the details of the air bearing mobility unit are described in Reference 2. Briefly, the mobility unit, shown in Figure 2-31, provides for 5 DOF (not Z) mobility of a remotely controlled vehicle such as the TMS. The unit is outfitted with a radio controlled pneumatic thruster system, television cameras, docking probes, and mission specific test equipment such as docking aids and special grapple fixtures. The mobility unit is operated from a remote control room by a test subject using joysticks, controllers and video scene feedback. The control room contains dual joystick controllers and monoptic black and white television feedback for the operator as well as test and communications equipment for the experimenter.

The current test series required that the test operator control the mobility unit in an approach trajectory with respect to the MMS mockup, and at final approach accomplish a secure mating with a minimum of two of the three docking probes.

Six fully trained subjects (three males, three females) participated in the test series with each subject completing 54 approach and docking trials under the following conditions:

Control Variables

- Fixed distance for initial separation of MU and MMS - 8.2 m (27 ft.)
- Fixed output pressure per pulse for any one thruster - 1 ft.lb.
- Ambient lighting level on the task scene - 24 m (80 ft.)
- Video broadcast signal calibrated during system warmup for 4.5 MHz analog signal with a S/N ratio > 50 dB
- Fixed locations of television cameras on MU. Three cameras, one center mount and two side mounts, used two at a time
- Environmental control in the operator's station with respect to noise, illumination, temperature, and humidity to reduce effects of these extraneous variables.

Independent Variables

- Initial orientation of the MMS mockup with respect to the MU Line of Sight (LOS)
  - Offset left 35^{o}
  - Centered on LOS
  - Offset right 35^{o}

  (See Figure 2-32).

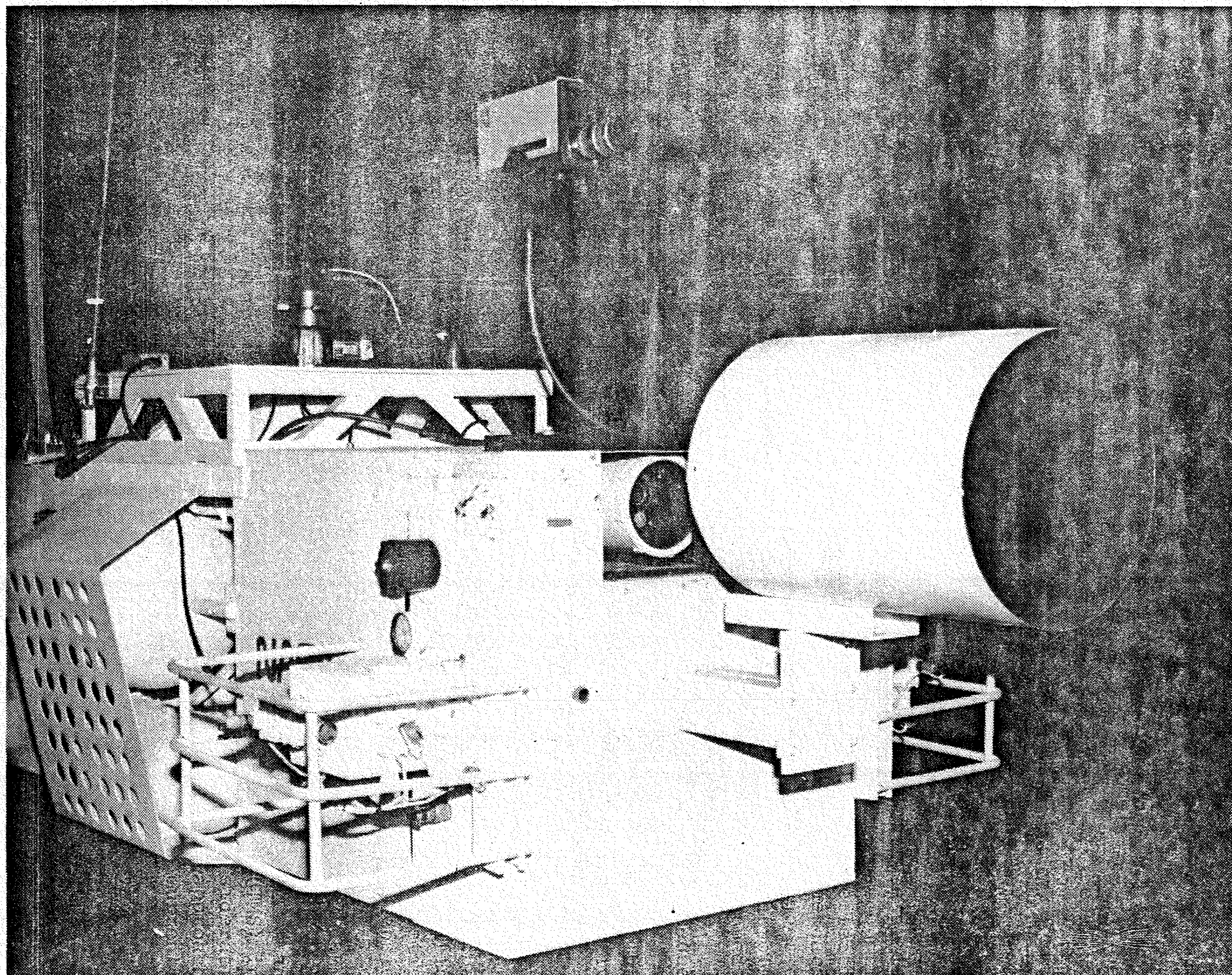

Figure 2-31: Mobility Unit Outfitted with Can-Type Capture Device

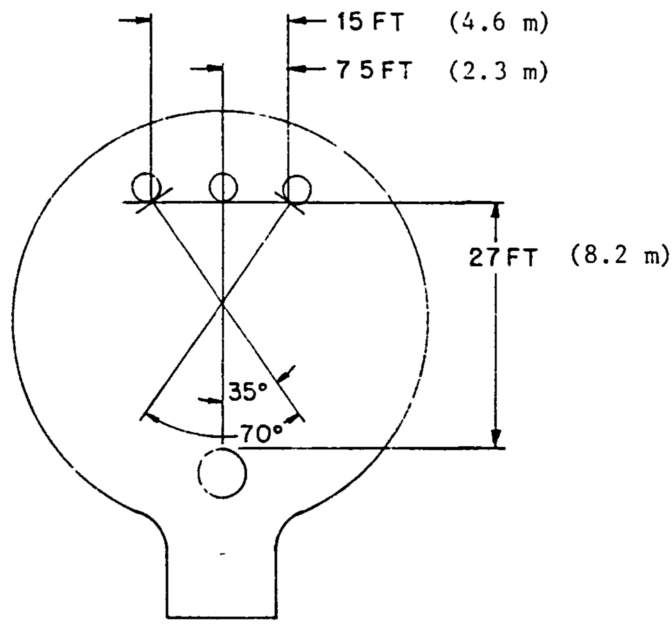

Figure 2-32: Approach and Docking Study Initial Conditions

Independent Variables (continued)

- Frequency of thruster firings in pulses per seconds
  - 3 Hz
  - 5 Hz
  - 7 Hz

- Camera pair configuration for video feedback
  - Center camera and right side camera
  - Center camera and left side camera
  - Center camera and switching to either left or right side camera.

Dependent Measures

- Resources expended for a successful docking of the MU with the MMS
  - Time to dock
  - Fuel to dock

- Additionally, the number of aborted attempts was recorded, the order of docking pin capture was noted, and the number of video switchings was recorded as supporting test data. These data were not considered for primary analyses of the test results.

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Each subject completed two replications of each combination of conditions for a total of 54 trials (2 replications x 3 target orientations x 3 camera conditions x 3 pulse frequencies). The order of presentation was randomized for each trial and for each subject.

2.2.3 Results

The data were subjected to the analysis of variance and F test to determine significant main effects of target orientation, pulse frequency, and camera pair on the time and fuel an operator required to perform a successful dock. The results of these analyses are presented in tabular and graphic form to demonstrate some of the resultant trends.

If we examine how varying the pulses per second of thrust affects performance, we see the following results from our test data:

- Times to perform at 3 and 5 pulses per second are closely correlated with each other.
- Time to perform at 7 pulses per second is generally a little longer than at 3 or 5 pulses.
- Generally, fuel consumed is equivalent for all three pulse frequencies.
- There is a tendency for 5 pulses per second to hold a slight advantage in overall performance.
- There is a consistent and overriding effect of approach orientation with a centered approach yielding superior performance.
- There are only slight effects of camera location, and these vary among other conditions.

These compounded results are graphically presented in Figure 2-33, which shows the trends among all of the variables of interest. It is apparent that there are fairly consistent interactions between pulse frequency and initial approach orientation, and these interactions are examined in Table 2-1. The effects for both variables are statistically significant, with centered approach demonstrating better performance and a pulse frequency of 7 Hz requiring more time for successful dockings. Figure 2-34 shows this in graphic form.

When fuel consumption is examined for the same conditions, we see similar results for approach orientation but not for pulse frequency. Table 2-2 and Figure 2-35 illustrate this, with a close nesting of pulse curves but significant variance attributed to approach orientation. When fuel consumption is considered, then, a straight-on final approach appears to yield fuel savings when compared to approaches off center by 35°.

Camera pair location did not demonstrate any significant influences on performance of this task, either as a main effect or in interaction with other variables.

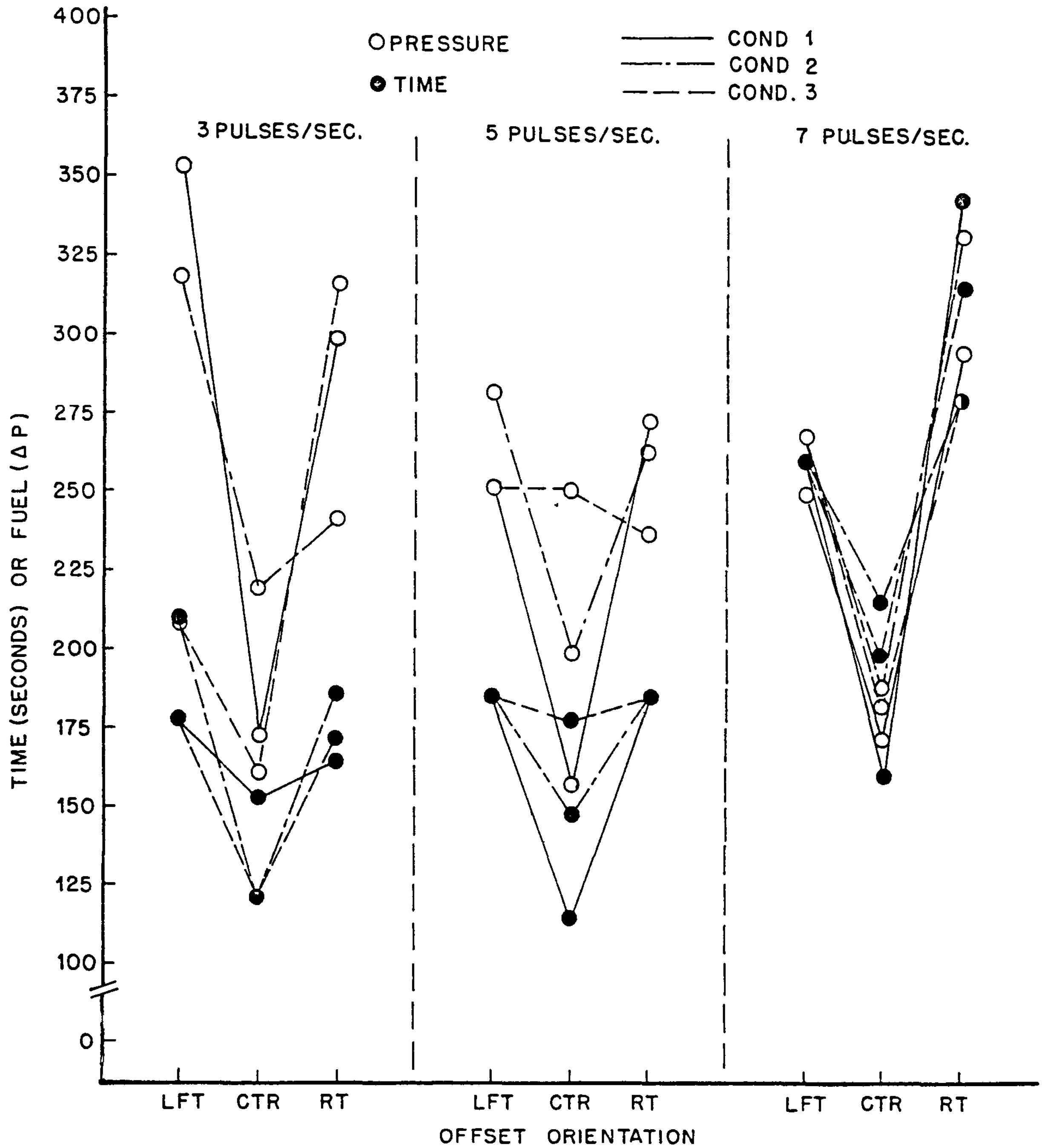

Figure 2-33: Effects of Offset Orientation and Pulse Frequency on Time and Fuel Expended to Accomplish Docking Task

Table 2-1: Effects of Pulse Frequency and Approach Orientation on Time to Perform Successful Docking (Time in Seconds)

Approach Orientation

Pulse Frequency	Left	Center	Right
3	188.67	131.55	174.67
5	185.75	146.55	183.14
7	263.36	188.19	313.72

	$\bar{x}$	197.29		
	s^2	2868.85		
	SS	25819.66		
	CSS	8074.59		
	RSS	15104.74		
* Significant at 90%	F_c	6.12		Orientation
		Q(F)	.06	
** Significant at 95%	F_R	11.44		Pulse
		Q(F)	.02	

Table 2-2: Effects of Pulse Frequency and Approach Orientation on Fuel Consumption for a Successful Docking (Fuel in ΔP-PSI)

Approach Orientation

Pulse Frequency	Left	Center	Right
3	294.45	184.03	284.03
5	263.19	201.39	256.25
7	255.56	178.47	300.70

	$\bar{x}$	246.45	
	s^2	1962.95	
	SS	17666.52	
	CSS	15522.90	
	RSS	300.24	
***Significant at 99%	F_c	16.84	
		Q(F)	.01
N.S.	F_c	.33	
		Q(F)	.74

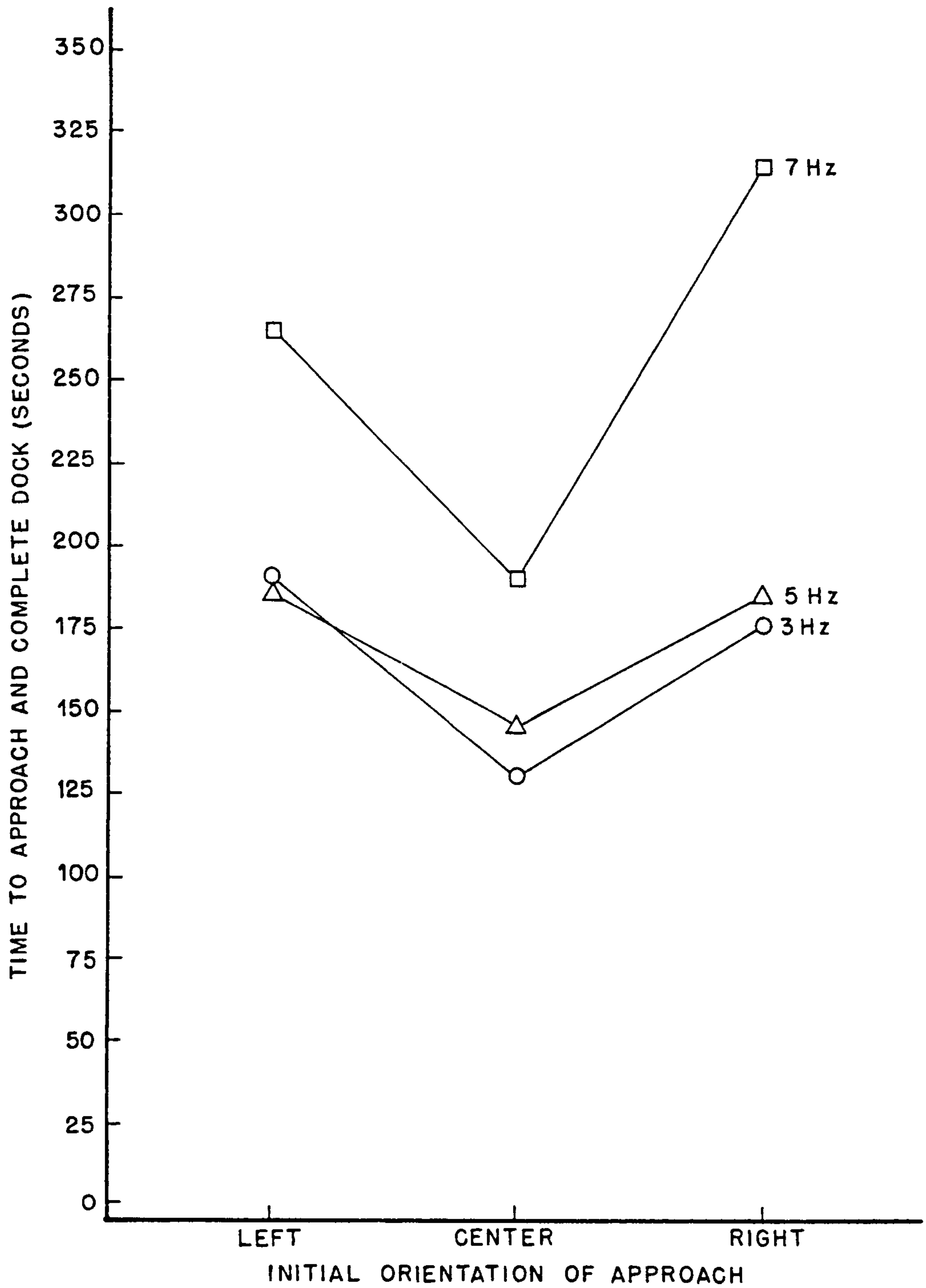

Figure 2-34: Effects of Offset Orientation on Time to Accomplish Docking Task

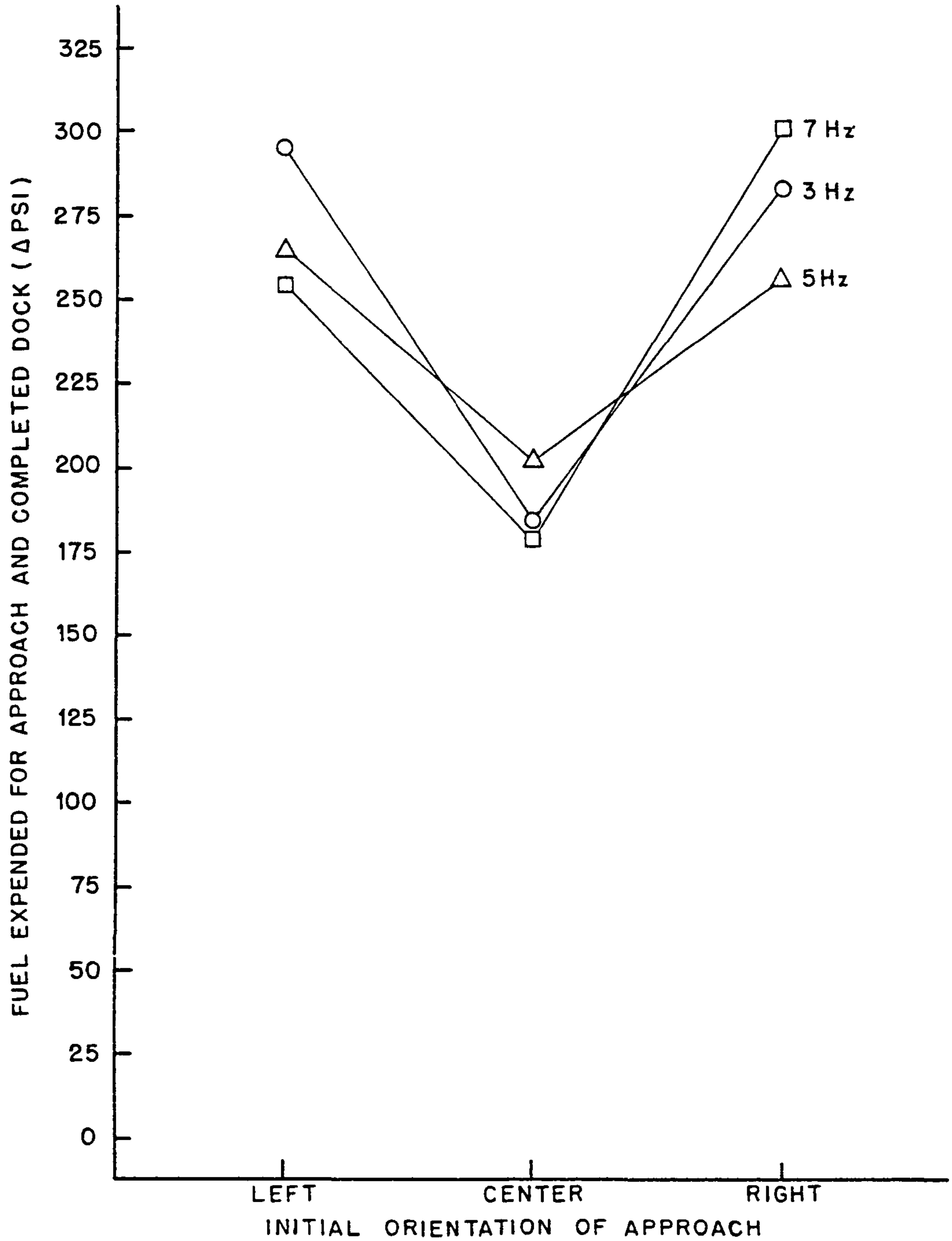

Figure 2-35: Effects of Offset Orientation on Fuel Expended to Accomplish Docking Task

The conclusions we can draw from this test series can be summarized as follows:

- Final approach orientation in a docking task should be made in line with the target docking probes.

- Propulsion thrust frequencies for thrusters generating 1 ft.lb. of thrust should be in the range of 3-5 Hz to reduce performance time.

- Camera pair location utilizing a center camera and either a left or right side camera does not appear to be a significant factor.

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3.0 VISUAL SYSTEM EVALUATION LABORATORY

The technical effort in the Visual System Evaluation Laboratory addressed the issue of stereoptic displays and operator perception of stereoptic image discrepancy. The fact that current stereoptic display systems being considered for teleoperator missions employ a dual sensor and dual monitor system has led to some concern over image discrepancy between the two sensors of the two display channels. Vibration and high G forces during launch, and operator manipulation of the two sensors during operations are some potential sources for system image discrepancies. The question arises as to how much discrepancy between the two images is necessary before the operator detects the discrepancy, and after that, what effects levels above this minimum detectable discrepancy in stereoptic imaging have on task performance.

Two evaluations were performed concerning these issues: (1) detectable stereoptic image discrepancy, and (2) effects of stereoptic image discrepancy on task performance.

3.1 DETECTABLE LEVELS OF STEREOPTIC IMAGE DISCREPANCY

The objective of this initial evaluation was to determine the operator-detectable threshold for size discrepancy between two displayed images viewed concurrently. A 2.3 cm (9 in.) diameter plate painted flat white at .9 reflectance was used as the task target. It was mounted vertically on a flat black task board 228 cm (90 in.) from a stereoptic pair of Cohu 2000 black and white vidicon cameras. The alignment, separation and convergence of the two cameras with respect to one another were controlled by reciprocally interlocking geared plates. Each camera was equipped with a zoom lens and a remote control for setting the lens over a range of 20 to 8 mm. Iris, focus, target sensitivity and contrast control for each camera were at the disposal of the experimenter during system calibration. The camera pair was mounted on a heavy duty tripod secured to the floor, and the center of the camera lens was aligned with the center of the task target. Convergence of the stereo pair was at 178 cm (70 in.) from the camera faces.

The images from the two cameras were routed to an experimenter's console where the images for the left and right cameras were displayed on separate monitors, either of which was selectable on a third monitor. The third monitor was also equipped with a pulse width detector. This detector was a pair of electronic gates through which the electron beam passes during a sweep across the monitor. Associated with each of the two gates was an electronically generated vertical line on the monitor which could be moved across the monitor face to the left or right. This provided a visual reference to the experimenter as to the "location" of the gates and consequently allowed measurements of TV displayed objects to be taken.

Procedurally, the experimenter aligns the left gate line with the left edge of the displayed target and the right gate line with the right edge of the target. As the electron beam passes through the first gate, it turns a pulse counter on, and as it passes through the second gate, it trips the counter off. The pulse width is then displayed in micro seconds--that is, the time it took the beam to pass through both gates. This measurement feature for the experimenter allows the displayed images from each camera to be very carefully calibrated with virtually identically sized images being transmitted to the subject, or images of a known discrepancy being transmitted. The experimenter adjusts the size of either the right or left image by changing the zoom setting on the appropriate camera to a predetermined size prior to transmitting the image to the subject.

3.1.1 Evaluation Procedure

The subject was seated in an isolated viewing room equipped with a Fresnel lens, two channel TV display. The technical description of this Fresnel TV system is given in References 3 and 4. The subject was also provided with a remote zoom lens control for either the left or the right camera, dependent upon the experiment conditions.

The experimenter set one of the displayed images--either right or left channel--to a prescribed size. The range of target sizes varied from 4.8 cm (1.89 in.) to 11.52 cm (4.54 in.) in diameter. The other image was set at a value greater or smaller in size than the first image by manipulating the zoom setting, and when the relative condition of the two images was correctly set, the experimenter transmitted the dual signals to the subject.

The subject's Fresnel system optically combines the right and left channel at the display face, presenting the right channel to the subject's right eye and the left channel to the subject's left, permitting the subject to perceive the task scene in three dimensions. The two images, however. are different sizes, and it was the subject's task to manipulate the size of one of the images via the zoom control--either left or right--so that any perceived differences were nulled out. This task, then, was operator dependent with no assumptions being made as to how great or small a difference might be detectable between images. The displayed image differences at the end of each trial were recorded by the experimenter, and the next trial was set up.

Each of four subjects completed three randomized replications of 25 different target sizes. All subjects were screened for normal vision. The subjects were all male, had technical backgrounds, and had participated previously in visual laboratory studies, so they were familiar with the subject's station and equipment.

Prior to any test run, all laboratory equipment was turned on, warmed up, and calibrated for TV linearity, focus, target sensitivity, and iris setting. The check-out and calibration procedures are detailed in Reference 3.

3.1.2 Evaluation Results

The subjects all employed a strategy of moving the image over which they had control back and forth through the reference image until any perceived differences were nulled out. Time to perform this approximation was specifically excluded as a variable, so the subject could take up to two minutes to get as precise an image equivalency as he could perceive. Table 3-1 gives the 25 target sizes employed in terms of pulse width, physical diameter, and the mean response in terms of pulse width of four subjects completing three replications. Since the eye resolves target size in terms of target area, the pulse width measure for the reference target and subject controlled target has been converted to target area. This percent agreement between the reference and response target area is shown in Table 3-2. Percent error ranges from 3.7% to .1% of the compared target areas with an average error of 1.8% for the displayed target sizes investigated. This implies some fairly stringent requirements on the two sets of sensor and display equipment in terms of alignment and calibration. In order to determine the effects of at least this much stereoptic image discrepancy on operator performance, a second stereoptic discrepancy test was undertaken.

3.2 TASK PERFORMANCE AS A FUNCTION OF STEREOPTIC DISPLAY DEGRADATION

From the aforementioned investigations dealing with operator perception of the equivalency of televised stereoptic images, it had been determined that mean errors between two displayed target areas can be 1.8% and still be reported as being equal by the human operator. This difference in target areas can be taken as a threshold measure which gives an indication that area differences less than 1.8% will generally not be noticeable by the operator for simple targets. However, this detectable difference threshold does not indicate how stereoptic discrepancy will affect operator performance. In order to determine this effect, the following experiment was conducted.

3.2.1 Evaluation Procedure

The subjects who completed the first stereo evaluation were also used to complete this second evaluation.

For each trial, two targets were positioned on a task board for display to the operator. One target was a 7.62 cm (3 in.) cylinder outfitted with appendages to simulate a satellite configuration; the other was a plain 7.62 cm (3 in.) diameter cylinder. The satellite target was affixed to a target motion generator which provided for fore and aft motion along the camera LOS. The cylindrical target was mounted on a tripod for manual positioning about the task board by the experimenter. This reference target was positioned in the horizontal plane with, and either to the right or left of, the subject-controlled target.

The task involved having the subject move the movable target fore or aft until it was aligned with the face of the reference target. This procedure has been followed in a number of other stereoptic tests (References 5 and 6). However, one camera/display subsystem was purposely out of calibration by a

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Table 3-1: Size of Displayed Targets Compared with Mean Response Target Sizes

	Actual Displayed Target Size (In Pulse Width)	Actual Displayed Target Size (Diameter in In.)	Mean Response Target Size Pulse Width
1	13.0	1.890	13.12
2	13.4	1.948	13.45
3	13.7	1.992	13.68
4	13.8	2.007	13.99
5	14.0	2.036	13.88
6	17.0	2.472	16.96
7	17.5	2.544	17.61
8	17.9	2.603	17.73
9	18.1	2.632	17.79
10	18.3	2.661	18.09
11	21.0	3.053	20.91
12	21.6	3.141	21.59
13	22.1	3.213	21.79
14	22.3	3.242	21.88
15	22.6	3.286	22.24
16	25.0	3.635	24.76
17	25.7	3.737	25.33
18	26.3	3.824	26.27
19	26.6	3.868	26.58
20	26.9	3.911	26.63
21	29.0	4.217	28.98
22	29.8	4.333	29.22
23	30.5	4.435	30.07
24	30.9	4.493	30.78
25	31.2	4.536	30.78

Table 3-2: Actual Target Area and Reported Target Area with Percent Agreement Between Areas

	Actual Displayed Target Area (Sq. In.)	Computed Mean Response Target Area (Sq. In.)	Percent Agreement of Actual vs Reported Target Area
1	2.806	2.858	98.2
2	2.981	3.004	99.2
3	3.116	3.107	99.7
4	3.162	3.250	97.3
5	3.254	3.199	98.3
6	4.799	4.776	99.5
7	5.085	5.149	98.8
8	5.320	5.220	98.1
9	5.440	5.255	96.6
10	5.561	5.434	97.7
11	7.322	7.260	99.1
12	7.747	7.740	99.9
13	8.110	7.884	97.2
14	8.257	7.949	96.3
15	8.481	8.213	96.8
16	10.378	10.180	98.1
17	10.967	10.653	97.1
18	11.485	11.459	99.8
19	11.748	11.731	99.9
20	12.015	11.775	98.0
21	13.964	13.945	99.0
22	14.745	14.177	96.1
23	15.446	15.014	97.2
24	15.854	15.731	99.2
25	16.163	15.731	97.3
		Overall Agreement	98.2

pre-determined amount. This calibration error varied from 0% to 24% of the differences between displayed target areas.

During the task, the operator understood that time to perform the task was, again, being excluded as a variable and that he could take as much time as he wanted to accomplish the target alignment. When the operator reported that the targets were perceived as being aligned, the video to the operator was terminated and the experimenter measured the discrepancy in alignment between the two targets. Error measure was then manipulated to determine the effects of stereoptic image discrepancy on operator performance.

3.2.2 Evaluation Results

The mean absolute and mean signed alignment errors for each case of image discrepancy are shown in Table 3-3. The absolute error represents the mean magnitude of alignment error without considering direction, and signed error represents the average error in either the positive or negative direction, which accounts for its smaller value. The range of alignment errors for each case of stereoptic discrepancy is shown in Table 3-4, along with the actual percentage image discrepancy. Figure 3-1 shows these ranges in graphic form with the mean signed error for comparison. Figure 3-2 shows the mean absolute error as a function of percent image discrepancy. The trend noted in this figure is that alignment error increases at a gradual rate as image discrepancy increases. These results could be expected, although the gradual rise in the trend line indicates that performance is not sharply affected by increasing discrepancy.

The data from the first evaluation suggest that operators will perceive relatively small stereoptic image differences (less than 2% difference of displayed image areas), and the data from the second evaluation suggest that these apparent difference will affect alignment task errors the percent discrepancy increases. However, the effect is a gradual increase in errors when compared to the 20% increase in image discrepancy.

Table 3-3: Mean Absolute and Mean Signed Alignment Errors

SIZE OF COMPARISON TARGET (Diameter in μ sec)	SIZE OF TEST TARGET (Diameter in μ sec)	MEAN ABSOLUTE ALIGNMENT ERROR FOR TWO TARGETS (in mm)	MEAN SIGNED ALIGNMENT ERROR FOR TWO TARGETS (in mm)
9.4	9.4	3.54	- .56
	9.6	4.15	- 1.67
	9.8	4.74	- .70
	10.0	5.08	- 1.92
	10.2	3.85	- 1.95
9.0	9.0	2.61	- .01
	9.2	4.67	.31
	9.4	4.29	- .59
	9.6	5.35	- .63
	9.8	5.43	- 1.03
8.6	8.6	3.66	2.78
	8.8	2.17	- .55
	9.0	2.46	.76
	9.2	3.06	- .30
	9.4	4.49	- .21
8.5	8.5	6.32	- 1.28
	8.7	5.89	1.70
	8.9	6.30	- .38
	9.1	7.33	- 1.11
	9.3	6.85	- .25
8.1	8.1	3.38	.14
	8.3	2.80	- 1.36
	8.5	4.53	- 1.93
	8.7	5.21	.17
	8.9	7.74	.30
7.7	7.7	6.62	.86
	7.9	3.00	.36
	8.1	2.61	- .27
	8.3	3.34	- .88
	8.5	4.95	.15
7.5	7.5	8.02	- 1.88
	7.7	7.34	- .02
	7.9	10.02	1.30
	8.1	9.31	3.35
	8.3	8.33	3.71
7.1	7.1	3.75	1.27
	7.3	5.38	1.46
	7.5	7.34	.24
	7.7	8.49	1.87
	7.9	8.97	4.21

Table 3-4: Range of Response Errors by Target Size and Actual Discrepancy Between Target Areas

DISTANCE OF TARGET TO SENSOR (in in)	SIZE OF COMPARISON TARGET (Diameter in μ sec)	SIZE OF TEST TARGET (Diameter in μ sec)	AREA OF DISPLAYED TARGET (Converted to sq in)	ACTUAL % DISCREPANCY IN AREA BETWEEN TWO TARGETS	RANGE OF RESPONSE FRRORS (in mm) +	-
67	9 4	9 4	1 467	0	5 0	- 7.1
		9 6	1 530	4	3 8	- 8.5
		9 8	1 595	9	5 1	- 7 7
		10 0	1 660	13	5 0	- 9 8
		10 2	1 728	18	5 0	- 11.0
70	9 0	9 0	1.345	0	6 5	- 3 3
		9 2	1 405	5	12 2	- 10.5
		9 4	1 467	9	9.2	- 5.8
		9 6	1 530	14	11 5	- 8 4
		9 8	1 595	19	12 5	- 10 2
73	8 6	8 6	1 228	0	8 2	- 3 8
		8 8	1 286	5	7 5	- 3 4
		9 0	1 345	10	7 0	- 3 2
		9 2	1 405	14	10 3	- 4 7
		9 4	1 467	20	13 5	- 8 7
75 5	8 5	8 5	1 200	0	14 5	- 16 0
		8 7	1 257	5	9 9	- 24 0
		8 9	1 315	10	8.9	- 75 5
		9 1	1 375	15	12 0	- 22 0
		9 3	1 436	20	17 5	- 12 0
78 5	8 1	8 1	1 089	0	9 5	- 5 0
		8 3	1 144	5	4 2	- 9.9
		8 5	1 200	10	9 9	- 18 0
		8 7	1.257	15	8 1	- 8 1
		8 9	1 315	21	14 0	- 20 0
81 5	7 7	7 7	984	0	18 0	- 7 5
		7 9	1 036	5	12 2	- 4 6
		8 1	1 089	11	8 5	- 4 3
		8 3	1 144	16	7 2	- 5 2
		8 5	1 200	22	10 8	- 5 3
84	7 5	7 5	934	0	12 5	- 14 5
		7 7	984	5	9 2	- 7 5
		7 9	1 036	11	14 0	- 13 5
		8 1	1 089	17	18 0	- 13 2
		8 3	1 144	23	13 0	- 7 5
87	7 1	7 1	837	0	11 4	- 4.3
		7 3	885	6	11 9	- .6 1
		7 5	934	12	13 8	- 7 5
		7 7	984	18	17 8	- 7 5
		7 9	1 036	24	18 3	- 7 5

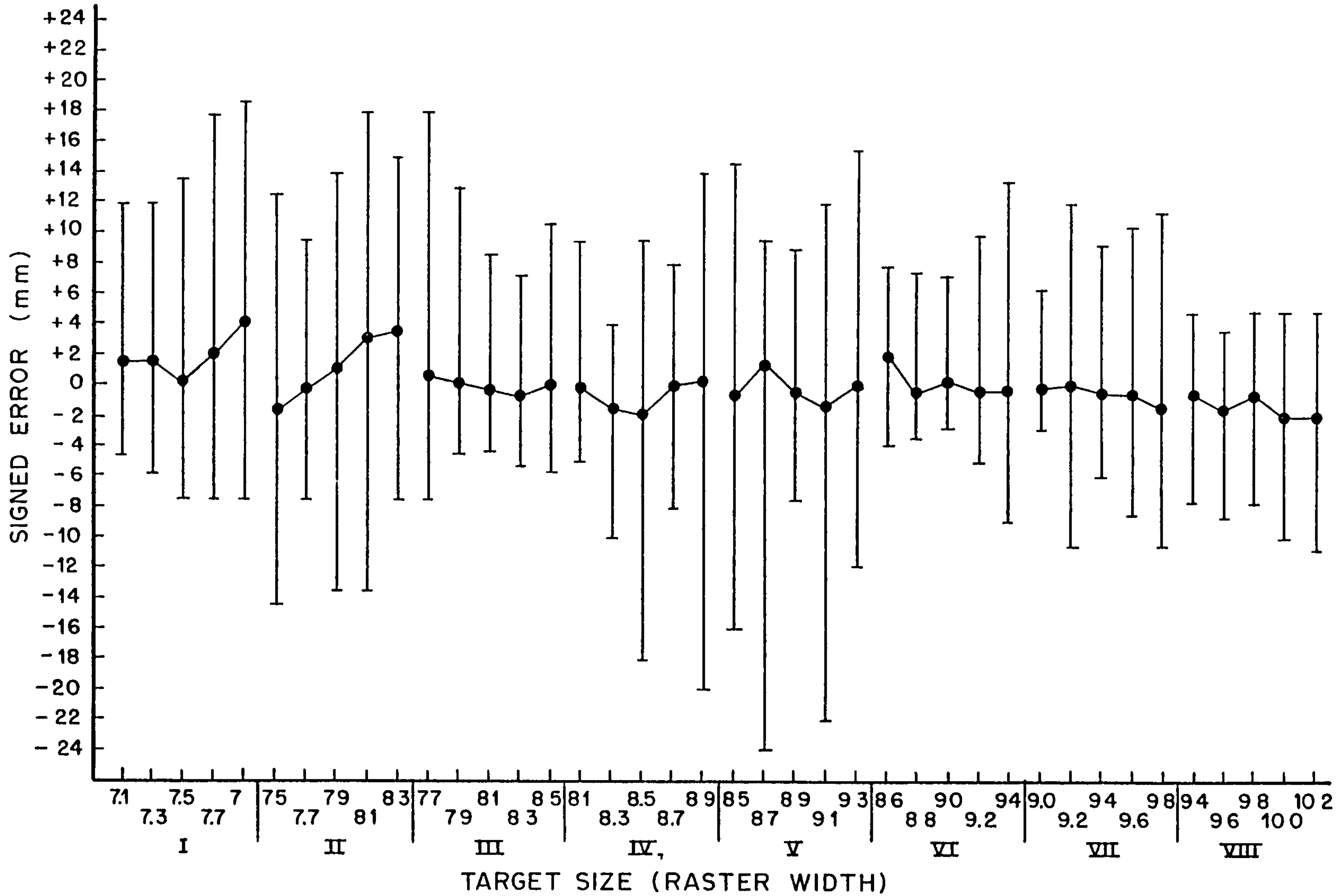

Figure 3-1: Range and Mean Signed Error of Alignment by Target Discrepancy

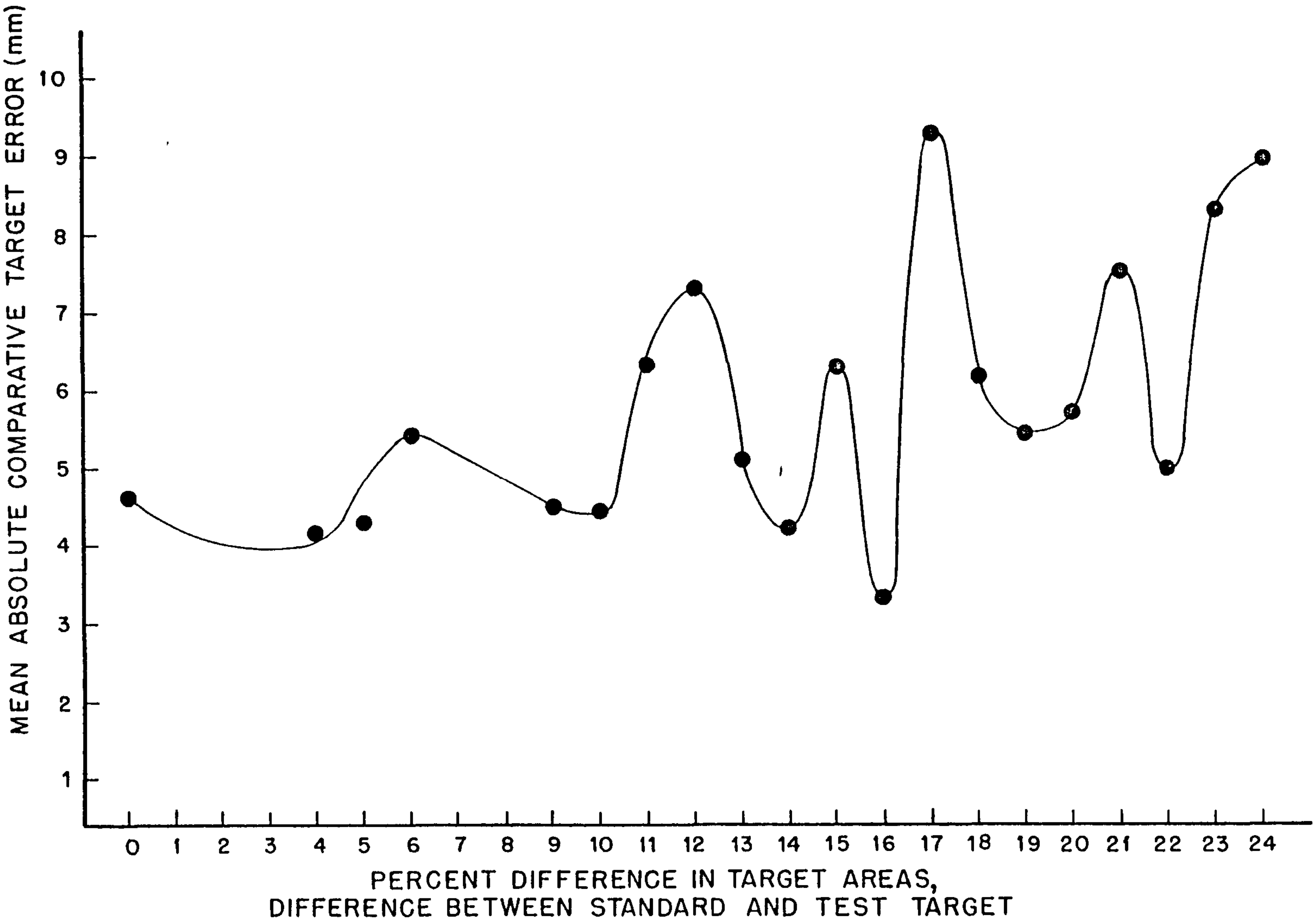

Figure 3-2: Mean Absolute Error as a Function of Percent Image Discrepancy

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4.0 MANIPULATOR SYSTEM EVALUATION LABORATORY

The Manipulator System Evaluation Laboratory has been the focal point for the evaluation of controllers, manipulator arms, end effectors, and aided control systems at remote task sites using television systems previously evaluated in the visual system evaluation laboratory for scene generation. This permits a good estimate of the overall variance in performance as a function of different visual systems, and it allows the residual variance to be ascribed to differences in manipulator systems employed in remote tasks. Another source of variation in the evaluation of manipulator systems comes from differential skill and training levels of subjects/operators. During 1979, a subject pool of qualified manipulator operators was formed and processed through training to ensure an adequate source of operators for evaluation of manipulator systems.

4.1 SUBJECT TRAINING

Twelve potential operators were selected from a group of volunteers from within the technical laboratories at MSFC. All subjects had a technically-oriented educational and work background and had previously participated in teleoperator studies. Following initial screening for visual acuity, stereoptic vision and right-handedness, a total of eight subjects (three female and five male) was selected for manipulator training on the Protoflight Manipulator Assembly (PFMA). The PFMA, as it was used during subject training, is shown in Figure 3-1. Control of the PFMA was managed from the remote operator's control apparatus, including the video system and the communication system, and the test subject was allowed to exercise the equipment under the direction of a test director. During this initial exercise period, all obstructions in the manipulator room were removed from within the working envelope of the manipulator to prevent inadvertent damage to the arm. Once the operators were comfortable utilizing the TV system, the communications gear, and the single hand controller (shown in Figure 4-2), they were allowed to practice tip placement of the PFMA, again under the direction and following the instructions of a test director. The outcome of these exercises was a report by each subject that he or she felt comfortable with the equipment and could use it to control the manipulator arm.

Following this report, the subjects were asked to perform ten trials on a simple task board. The task involved moving the PFMA tip from one 3.18 cm (1.25 in.) diameter target to another in a sequence determined by the test conductor. The test setup is shown in Figure 3-3. Initially , each subject performed 10 sequences of 15 targets each, and time to move and response accuracy were plotted to determine the learning trend for each subject. If performance (time and accuracy) did not vary as much as $\pm$ 2.5% over the last three recorded trials, it was then assumed that training for that subject was sufficient for operational tests in the future. If more than ten trials were required for a subject's learning curve to approach the asymptote, then the test director proceeded until variation for the last three trials was within the 5% limit.

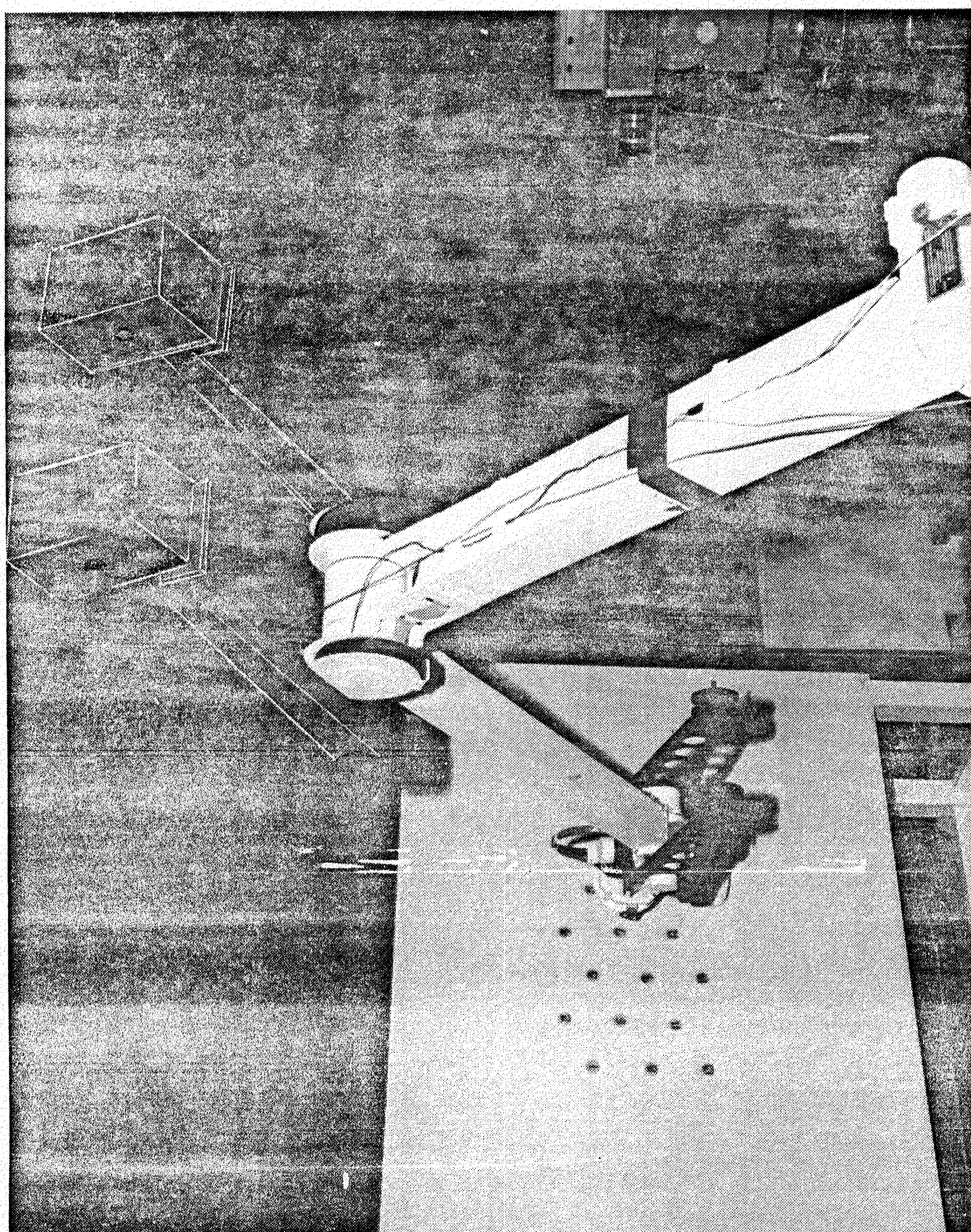

Figure 4-1: PFMA During Performance Training Trials

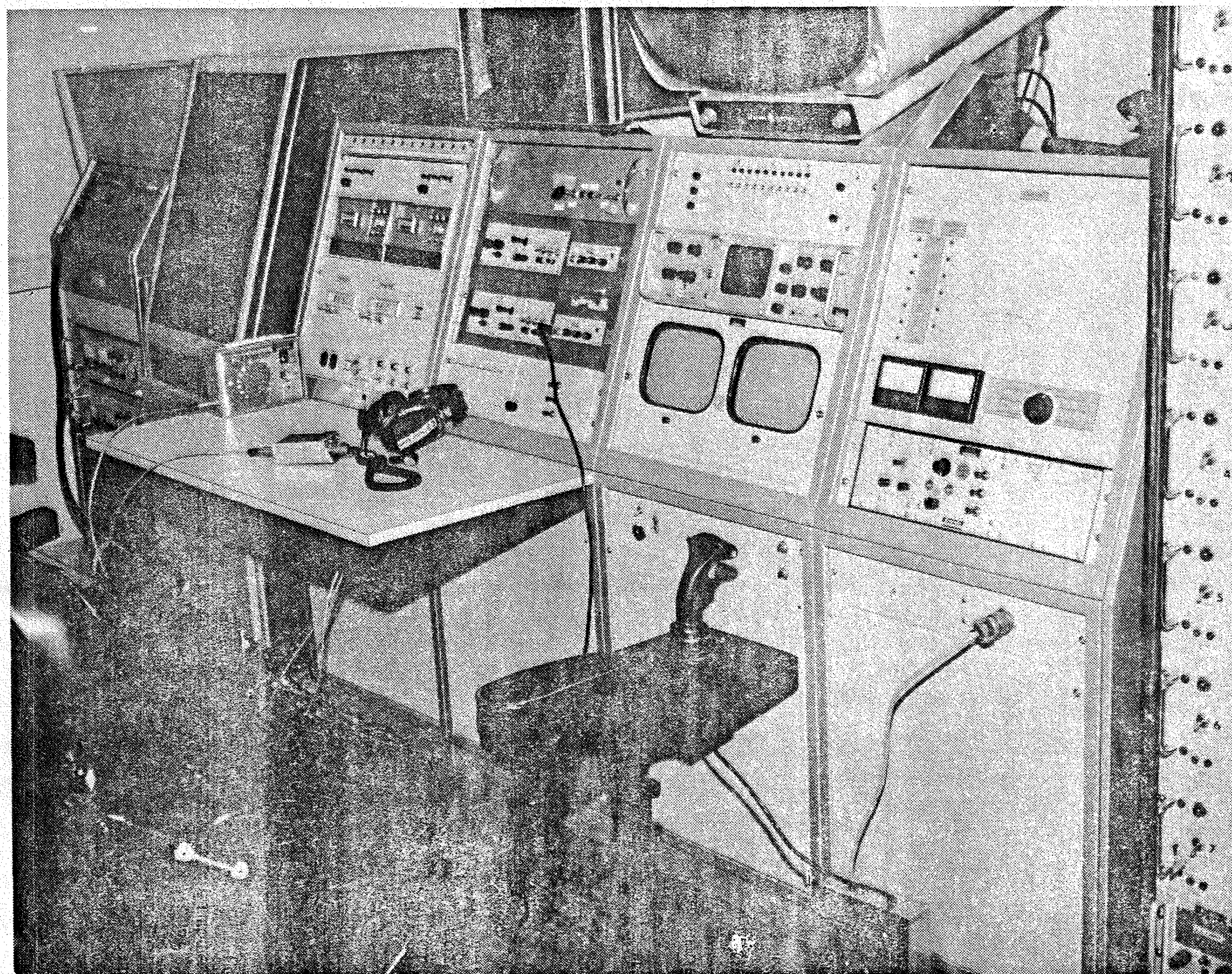

Figure 4-2: Manipulator Operator's Control Console

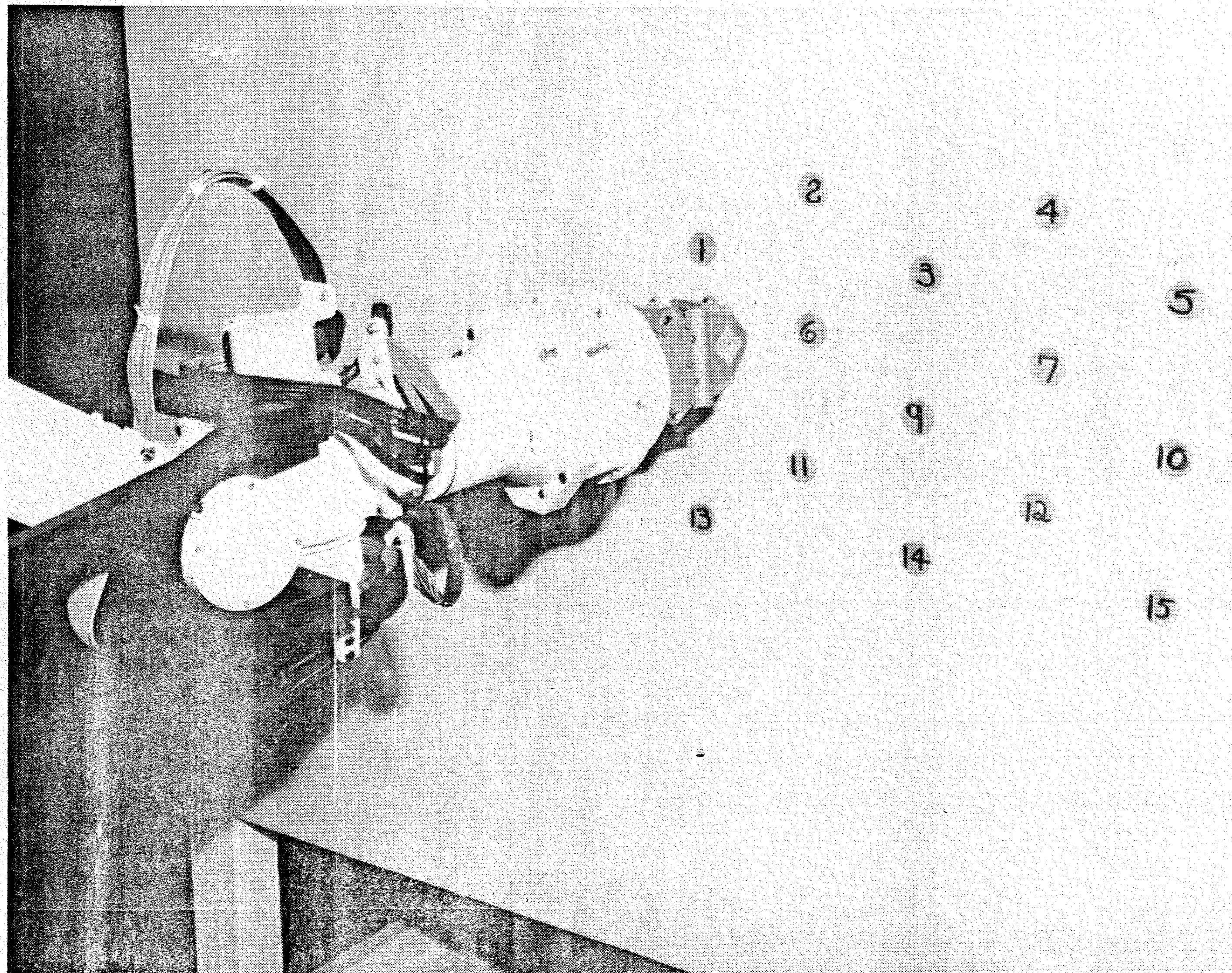

Figure 4-3: PFMA Touching Test Index Points During Tip Position Training of Operators

4.2 LABORATORY STATUS

This initial selection and training of the subject pool was the only accomplishment using the PFMA. Unfortunately, a fragile elbow gear cracked and then broke into several sections during test and checkout of the PFMA. The PFMA was then returned to the manufacturer for replacement of a modified elbow gear ring, and the PFMA operating procedures were modified to preclude this type of problem in the future.

The subject pool is available for participation in the manipulator system evaluations at such time as the PFMA is returned to MSFC. Test plans and test apparatus are all prepared for testing as described in References 7 and 8.

5.0 TELEOPERATOR TECHNOLOGY DEVELOPMENT OF PROGRAM REQUIREMENTS

During 1979, considerable interest was shown in the MSFC teleoperator and robotics capabilities. On-site visits were made by representatives of other NASA centers, by ESA representatives, by technical personnel involved in the manufacture of the Remote Manipulator System (RMS), and by NASA Headquarters personnel. Some of the demonstrations conducted for these visitors involved specific applications of teleoperation, such as the teleoperator docking with, and retrieval of, the Goddard Multimission Modular Spacecraft (MMS), while some dealt with very broad based issues such as the development of a fully integrated robotics laboratory for European space research.

MSFC's ten year involvement in laboratory studies of teleoperator capability is a valuable resource for others interested in remotely conducted tasks. In helping to maintain this position in robotics and teleoperation, Essex performed several tasks which contribute to the teleoperator technology development design bases.

The requirement for an integrated test facility for robotics and teleoperators was identified, and the specifications for such a facility were solicited from the several technical teams involved in teleoperator research. Essex proposed that such a facility should be:

- A dedicated facility where robotic and teleoperator research and applications are the principal program concerns.
- A facility capable of exercising the current hardware systems and also capable of integrating new systems at some later date.
- A facility that can accommodate several simultaneous investigations at the subsystem level and a fully integrated system level evaluation.
- A facility that can accommodate support systems such as automated servicers, beam builders, large attached manipulator arms, and specific spacecraft models.
- One that permits extensive teleoperator mobilty on a one-to-one scale, that is, maneuvering 20-35 m using full scale mockups.
- One that provides computer hardware and software to support the total range of teleoperator control concepts from fully automated servicers through operator/computer symbiosis in operations to fully human operator controlled tasks.

- One that provides simulation of six degrees of freedom in guidance and control of test vehicles.

- One that incorporates the capability to evaluate the full range of potential visual systems being considered for remotely controlled operations.

- One that provides for operator aids such as range finders, range/rate sensors, radars, laser instruments, and graphic displays.

- One that provides for the full range of potential manipulator and controller systems being considered for remotely controlling robotic and teleoperator tasks, and

- One that provides for appropriate mission simulation using less than full scale mockups and vehicles.

During the design basis task, Essex developed a scale model laboratory mockup that provided for most of these capabilities and also developed technical summaries of some of the significant support items that should be considered for the robotics laboratory. These technical summaries follow.

ESSEX

TECHNICAL SUMMARY

Component Name - Air Bearing Epoxy Flat Floor

Technical Description - The proposed air bearing floor is a 23 x 15 m (75 x 50 ft.) hard, black epoxy surface with a surface anomaly limit of .00254 cm per 3.1 m (10 ft.) diameter. This surface will provide a surface on which to exercise six degrees-of-freedom mobility units supported by air bearing pads. The epoxy must be poured over a homogeneous foundation to prevent anomalies from developing as a function of differential expansion coefficients of different materials in the foundation. A candidate epoxy is the Moran type 109B71.

Functional Objectives - The air bearing floor will provide a test surface on which air bearing vehicles can be floated for remotely controlled maneuvers such as rendezvous, docking and fly-around inspection. The smooth surface will provide a means to gain undisturbed lateral and translational motion from mobility units.

Simulation Objectives - The flat floor will support simulations that require the control of free flying vehicle maneuvers such as rendezvous, docking and servicing, and will permit evaluations of docking hardware and human performance in conducting remotely controlled tasks in the laboratory setting.

Relationship to Other Systems - Mockups of flight hardware can be mounted off the edge of the flat floor, and the flat floor can be used as a bed on which to fly satellite capture devices, docking probes and servicing vehicles, By inverting the thruster control schemes, the perception of "flying" the off-the-floor mockup can be induced to the human operator. It is expected that crew training for control of remotely manned vehicles can be conducted using the flat floor and appropriate mockups.

Anticipated Results of Simulations - The simulations will yield data on the effectiveness of human control over free flying vehicles. Although the flat floor will provide simulation of only the translational and lateral movements of a vehicle, additional degrees-of-freedom can be induced at the mobility unit, a feature discussed under Mobility Units. The specific results anticipated will be measures of effectiveness in two vehicle rendezvous approach and docking, and in single-vehicle maneuvers using varying control and controller configurations.

TECHNICAL DATA SUMMARY

Component Name - Free Flying Mobility Unit

Technical Description - The Mobility Unit is a piece of equipment designed to permit pitch, yaw and roll about a central axis of a teleoperator simulator, and translation and lateral movement through air bearing pads mounted in the base of the pedestal. The Mobility Unit upper bay, which is mounted on an air bearing sphere at the top of the pedestal, is equipped with 16 small thrusters which control the three attitudes via radio command. The air pad pedestal base, the center of gravity air bearing sphere, and the four groups of four thrusters permit free movement of the Mobility Unit in five degrees-of-freedom.

Functional Objectives - The Mobility Unit serves as a mobile test bed for camera systems, thruster control concepts, docking probes, target aids and similar subsystems which may be incorporated in a teleoperator system. It provides five degrees-of-freedom visual feedback to the operator through onboard TV cameras, and five degrees-of-freedom mobility through the onboard thruster system via operator command.

Simulation Objectives - The Mobility Unit is used to measure human operator effectiveness in controlling remote vehicles using televised scene feedback and hand controller inputs linked to onboard thrusters. The Mobility Unit is particularly effective for approach and docking simulations where several control concepts are being considered, or where docking aids are being evaluated.

The Mobility Unit can also have the control logic for the onboard thrusters inverted, and when a camera is mounted on a stationary base, the thruster control inputs made by the operator appear to be controlling the fixed base, such as a probe for docking. This additional capability which takes full advantage of the operator's perceptual capability and the Mobility Unit's motion has proven very useful in prior testing.

Relationship to Other Systems - The nominal configuration of the Mobility Unit is two center-mounted boxes. It is also possible to mockup other spacecraft configurations over the basic hardware which would serve the purpose of simulating specific missions. It is also possible to limit the three degrees-of-freedom about the central axis to simulate large mass spacecraft inertia.

Anticipated Results of Simulations - It is expected that the Mobility Unit will yield data concerning the effectiveness of selected thruster control modes in approach and docking tasks. It will also give an indication of how camera configurations on remote vehicles affect maneuvering tasks and how target and docking aids can be used to aid remotely controlled tasks. It will also provide data on the effectiveness of various control systems--joystick versus anthropomorphic controller, one hand versus two-hand control, etc.

ESSEX

TECHNICAL DATA SUMMARY

Component Name - Free Flying Target Assembly

Technical Description - Similar to the Mobility Unit, the target assembly is an air bearing pad with a central pedestal on which variously configured mockups can be mounted while free floating in two translational axes and having the capability to pivot around the central pedestal. The target assembly does not have thrusters for active motion and can only be acted upon by the influences of other, nearby vehicles.

Functional Objectives - The target assembly serves as a free floating base on which to mount target mockups, drogue fixtures, video links and similarly passive elements for appropriate free flying mission simulations involving other spacecraft.

Simulation Objectives - The target assembly will provide second vehicle attributes for human operator experiments involving approach, rendezvous and remote docking tasks. It will serve as a test bed for docking fixtures, target docking aids, and as a means to verify two vehicle interface components.

Relationship to Other Systems - The target assembly can take on the attributes of any small second vehicle system by outfitting it with an appropriate mockup. It can also simulate large mass targets through restrictions imposed on its onboard air bearing mobility system.

Anticipated Results of Simulations - It is expected that the target assembly, used in conjunction with the Mobility Unit, will provide a means of gaining human operator performance data in two vehicle maneuvers where one vehicle is under the active control of the operator and the other vehicle is subject to the influence of the first but not under active operator control.

It is also anticipated that the target assembly will be employed in space environmental studies such as solar lighting and thruster impingement.

TECHNICAL SUMMARY

Component Name - Protoflight Manipulator Arm Assembly (PFMA)

Technical Description - The PFMA is a modular, six-degrees-of-freedom anthropomorphic manipulator assembly having flexible joints for shoulder, elbow and wrist movement. The shoulder is capable of movement in the pitch and yaw axes. The elbow is capable of pitch movement with roll/indexing capability between the shoulder and elbow. The wrist assembly provides roll, pitch and yaw positioning of the end effector. The reach of the PFMA is over a range of 25 cm to 200 cm as measured from the shoulder pivot point through the wrist point. Total arm length, including wrist and end effector, is 3.05 m. Joint motion is accomplished through a system of gears and/or clutches and is powered by 28 Vdc reversible motors. The end effector has a parallel jaw activated through a spiroid gear set. An electronic interface package is part of the PFMA system. This interface has the power supplies for all joints on the PFMA, interface cards for the rate feedback resolvers, and additional space for position encoder electronics when they are added.

Functional Objectives - The PFMA serves as a general purpose manipulator testbed for studying human operator performance in manipulative tasks, end effector designs, interface requirements, and operator control concepts.

Simulation Objectives - The PFMA is used to study the tasks that can be accomplished by a general purpose manipulator. The PFMA can act as a platform for testing end effector designs such as the parallel jaw design and the inflatable end effector. It provides a manipulator which can be driven by several different hand controllers to determine the hand controller best designed for a particular manipulative task and as a manipulator system testbed to define the various types of tasks best suited to a general purpose manipulator.

Relationship to Other Systems - The PFMA, as configured, can provide a dynamic testbed for assembly tasks, repair and replacement tasks, and simulated "in space" movement of object tasks. It provides a means of defining what types of tasks can be carried out by a general purpose manipulator and is a platform on which combinations of end effectors, tools and manipulatable hardware can be studied. It is possible to use the PFMA to study operator-in-the-loop control as well as computer controlled tasks and computer augmented tasks. It may be controlled either by the Interface/Control System or through any conventional manipulator control system.

Anticipated Results of Simulations - It is anticipated that the PFMA will provide insight into end effector designs, hardware design for hardware to be manipulated by a general purpose manipulator, types of operator feedback from the manipulator to the operator or computer necessary for a particular task, the ability to define tasks which can be carried out under computer control and those tasks which require human intervention, and the necessary camera configurations and lighting conditions under which a wide range of tasks can

be carried out. The PFMA will answer many questions on the design of a general purpose manipulator, the tasks such a manipulator can carry out, and the tasks which can be done by other types of manipulators.

ESSEX

TECHNICAL SUMMARY

control station

Component Name - The Interface/Control System for the PFMA

Technical Description - The operator interface to the PFMA consists of a control console facility containing video monitors with controls and signal conditioning devices, a location for a human operator near the console, and a platform on which is mounted one of several hand controllers. The control for the PFMA is provided by a mini computer. The mini is either an SEL 840A or a PDP 11/34. The SEL 840A is a general purpose, 24 bit binary computer containing a CPU with 32K words of core memory, an SEL 520A Papertape Read/Punch, a Xerox Multiplexer/Digitizer 32 channel A/D converter, a 32 channel D/A converter, a pair of tape drives with controller, a serial printer with interface, a three Mbyte hard disk system, a Lear Siegler ADM-3A CRT terminal/operators console and RTOS operating software. The PDP 11/34 is a general purpose, 16 bit binary computer containing a CPU with Expander Box Power Supply, a DR411P Memory System, a dual Xebec 8" floppy disk system, a Kennedy Model 9300 Tape Drive, a Lear Siegler ADM-3A operators console and RSX-11 operating software.

Functional Objective - The Interface/Control System for the PFMA is designed so that various hand controllers and hand controller concepts can be tested with the PFMA. Various computer configurations can be used to interpret and condition the signals from the hand controller to the PFMA and from the PFMA feedback circuits to the computer or operator. Various control laws can be tested in all modes from joint-by-joint to fully automated computer control of the PFMA.

Simulation Objectives - The Interface/Control System is used as a testbed to compare hand controllers and control concepts such as rate controllers (stiff stick), position controllers (potentiometers), analog hand controllers, multiple hand controllers and toggle switches. The system provides a means of studying various control laws to determine an optimum algorithm and to use this algorithm to determine which tasks may be performed with the control laws. Finally, the system provides a means of fully automating the PFMA or any other manipulator for determining what types of tasks may be performed in an automatic mode and what types require some manual intervention.

Relationship to Other Systems - The Interface/Control System may interface with the PFMA or other manipulator arm for the purpose of determining an optimum set of operating characteristics and tasks to be performed.

Anticipated Results of Simulation - It is expected that this system will provide insight into human control of manipulator systems with varying levels of computer assistance. It will provide a testbed for studying various control laws and controller concepts and will contribute data on which to base the selection of the appropriate controller/control law depending on the requirements of the hardware and task combinations.

TECHNICAL DATA SUMMARY

Component Name - Bilateral Manipulator System

Technical Description - The Bilateral Manipulator refers to a class of two armed systems, usually in an anthropomorphic configuration, which is under the control of a single operator. The only differences between bilateral systems and single arm systems are functional in that bilateral systems permit holding, alignment, positioning with one arm while the other can carry out other tasks such as bolting, screwing, turning or multi-axis alignment much as humans do with their two arms and hands.

Functional Objective - Bilateral manipulators under the control of a single operator serve as advanced manipulator test beds for the performance of servicing tasks and other complex remotely controlled tasks. Prior manipulator system evaluations have dealt with bilateral arms operated with a computer interface between the arms and the human operator, and the potential for bilateral manipulator systems needs to be more fully explored.

Simulation Objectives - Tasks which require complex and dexterous remote manipulation such as servicing should be evaluated utilizing bilateral manipulator, with the results of performance being compared against similar tasks using a single manipulator arm. The simulations should address specific applications which reflect mission objectives in remote servicing. The objectives will center around construction of a data base which will permit design decisions to be made on operator performance measures for a given set of tasks.

Relationship to Other Systems - Bilateral manipulator incorporates many of the control features related to satellite capture and docking and retrieval devices wherein the operator is attempting to coordinate the simultaneous positioning of more than a single member at more than one point. It is anticipated that data generated using bilateral systems will provide insights into potential problems of docking and capture simulations.

Anticipated Results of Simulations - The foremost expectation is that comparative data can be gained which will be used as relative figures of merit for single versus bilateral manipulator systems employed in specific remotely controlled functions. These data can be used in developing design and mission criteria.

ESSEX

TECHNICAL DATA SUMMARY

Component Name - Visual Feedback Subsystem

Technical Description - The visual system is a complex of closed circuit television equipment which provides scene feedback to the operator of the relevant remotely operated task environment. The system is equipped with sensors, cabling, power supplies, signal processors and displays which permit a very wide variety of video signals to be transmitted and displayed to the operator, including monoptic/stereoptic, monochromatic and color, 4.5 MHz/1.0 MHz narrow band, varied S/N ratios, varied field-of-view, varied focal length, single and multiple sensors/displays, varied display aids, varied frame rates and varied sensor types.

Functional Objectives - The visual system is designed to provide scene feedback to the operator using state of the art television systems which are being considered as candidate sensor/display systems for teleoperator missions. The system contains the necessary equipment to provide for the study of all of the variables which may effect operator mission performance as a function of Visual Scene Feedback Subsystem.

Simulation Objectives - The primary objective is to study the effects on operator performance of a variety of visual subsystems used in teleoperator mission simulations. Since the primary mode of operator feedback is expected to be via video systems, the evaluations conducted have made extensive use of state-of-the-art video systems to determine a most effective sensor/processor/ display subsystem for the operator.

Relationship to Other Systems - Current evaluations have relevance in any system which relies on visual feedback to the operator as a primary mode of scene presentation. The present video subsystem permits parameter changes for simulations which can induce inverted operator perceptions such as "flying" a stationary camera or inspection of the underbelly of a satellite when the satellite mockup is being rotated. The video system can also be used in lighting studies to determine the effects of solar illumination and shadowing on video feedback.

Anticipated Results of Simulations - The primary result of video system simulations will be information related to the operator requirements for scene feedback which is adequate for mission functions. Much data has already been gathered on the perceptual capability of the operator to simulate proposed missions using specific satellite mockups and video feedback.

ESSEX

TECHNICAL DATA SUMMARY

Component Name - Orbital Servicer Unit

Technical Description - The Orbital Servicer Unit (OSU) is an engineering proof of concept unit which is designed to remove and replace modules at a prepared satellite. As currently envisioned, the OSU will be launched in the Shuttle bay with a specific set of replacement modules to accomplish a change-out/refurbish mission at one or more prepared sites. The OSU will be deployed from the Shuttle bay and with its on-board propulsion system be controlled to a rendezvous and dock with a target satellite. Guidance and control can be via ground uplink or Shuttle aft flight deck commands. Module changeout can be autonomously controlled by on-board microprocessors, or via operator command/control links. Following changeout, the OSU is returned to the Shuttle bay for deboost.

Functional and Simulation Objectives - The OSU engineering unit is being used to test out the concept of module replacement under microprocessor and human operator control using a six degrees-of-freedom manipulator. The functional and simulation objectives for the OSU are presently the same.

Relationship to Other Systems - The OSU, because it can be controlled from the aft flight deck, is related to Shuttle payload requirements and to payload crew operations requirements. Since it is designed to dock with and service only prepared sites, the OSU will be variously configured to dock with satellites and will be outfitted with mission dependent modules for refurbishment. The specific systems to which the OSU is related are still to be determined.

Anticipated Results of Simulations - Data on remote servicing in an autonomous mode and a human operator control mode will be the most extensive information gained from simulations. However, information on control algorithms and control software, module sizes and shapes, orifice configurations, electrical receptacle configurations, storage formats and other subsystem information will also be an integral part of the simulation results for analysis.

TECHNICAL DATA SUMMARY

Component Name - Beam Building Engineering Unit

Technical Description - The Beam Building Engineering Unit produces lightweight, triangular beams for large space systems (LSS) simulations. The triangular beams are continuously extended with struts affixed and can be cut to predetermined lengths.

Functional Objectives - The beam builder provides fabricated triangular beams for space structure assembly. It serves as an on-orbit manufacturing facility, converting its on-board and replenishable supply of aluminum sheeting into beams which can then be transported by the TRS to the construction site.

Simulation Objective - The simulations using the beam builder will focus on the TRS/beam builder synergism in a proof-of-concept simulation. The simulations will be ones in which the stationary beam builder feeds beams to the mobile TRS which then transfers them to the assembly site for structure assembly.

Relationship to Other Systems - The beam builder is one concept of a class of space structure applicances which is used in conjunction with teleoperator systems for the construction of large space systems.

Anticipated Results of Simulations - The simulations will yield systems data which describe the performance parameters of the beam builder/TRS/human operator in the simulated assembly of space structures. The most important information to be derived will be the measures of human operator performance in a complex, remote manipulation system task and a determination of what subsystems support the human operator will need to effectively perform large scale structure assembly with the aid of the TRS system.

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